Augmentation of Coronary Blood Flow by Intra-aortic Balloon Pumping in Patients After Coronary Angioplasty

Morton J. Kern, MD, FACC; Frank Aguirre, MD, FACC; Richard Bach, MD; Thomas Donohue, MD; Robert Siegel, MD; and Jerome Segal, MD, FACC

Background. Controversy exists regarding the ability of intra-aortic balloon pumping to increase coronary blood flow in patients with obstructive coronary artery disease. To assess the effects of intra-aortic balloon pumping on coronary hemodynamics, we measured coronary blood flow velocity with a 0.018-in. Doppler-tipped angioplasty guide wire in 15 patients who received an intra-aortic balloon pump for typical clinical indications.

Methods and Results. Intra-aortic balloon pumping augmented diastolic pressure 83±35%. In nine patients before angioplasty, peak diastolic coronary flow velocity beyond the stenosis (mean diameter narrowing, 95±7%) was 5.3±9.6 cm/sec and was unaffected by intra-aortic balloon pumping. After angioplasty, the improved coronary luminal diameter narrowing (n=12; mean narrowing, 18±12%) was associated with increased distal diastolic flow velocity integral and peak diastolic and mean velocities (13.3±8.4 units: 36.4±18.3 and 24.0±11.4 cm/sec, respectively; all p<0.01 versus before angioplasty), which were further augmented (36±37%, 54±49%, and 26±17%, respectively; all p<0.01) with intra-aortic balloon pumping. Intra-aortic balloon pumping did not significantly increase the distal systolic velocity integral (10±59%) or peak systolic velocity (3±33%). Similar degrees of balloon pump augmentation of distal coronary flow velocity values were observed in five angiographically normal reference arteries in four patients.

Conclusions. These data demonstrate lack of significant flow improvement beyond most critical stenoses with intra-aortic balloon pumping and the unequivocal restoration and intra-aortic balloon pump-mediated augmentation of both proximal and distal coronary blood flow velocities after amelioration of severe coronary obstructions in patients after successful coronary angioplasty. (Circulation 1993;87:500–511)

KEY WORDS • blood flow, coronary • intra-aortic balloon pump • angioplasty

Since initial studies two decades ago,1-3 controversy exists surrounding the ability of intra-aortic balloon pumping to increase coronary blood flow in patients who are critically ill or have significant atherosclerotic coronary narrowings. Human and experimental studies4-10 have provided conflicting data that are related, in part, to various indirect methodologies of measuring coronary blood flow. Previous investigations in our laboratory demonstrated significantly augmented blood flow velocities in the proximal portion of coronary arteries in seriously ill patients but could not address distal flow responses in the presence of obstructive coronary narrowings.11 With the advent of a small

(0.018-in.) angioplasty guide wire equipped with a 12-MHz Doppler tip, we have extended these earlier observations and, for the first time, measured coronary blood flow in the distal coronary artery in awake patients in an attempt to confirm one potential mechanism of benefit of the intra-aortic balloon pump. We tested the hypothesis that before angioplasty, distal epicardial coronary blood flow would be impaired and not be increased significantly during intra-aortic balloon pumping; after angioplasty, coronary flow would be increased and further augmented during intra-aortic balloon pumping. Data in support of this hypothesis would indicate that in most patients with critical coronary stenosis, intra-aortic balloon pumping reduces myocardial ischemia more by afterload reduction than direct coronary flow augmentation and that revascularization therapy will restore blood flow, which can then be further enhanced with intra-aortic balloon pumping.

Methods

The study group comprised 15 patients (Table 1) who had placement of an intra-aortic balloon pump for typical clinical indications [such as unstable angina (n=5), refractory hypotension after myocardial infarction (n=4), rescue angioplasty after thrombolytic therapy (n=4),12,13 or ventricular septal defect due to acute
myocardial infarction (n=2)]. The two patients with ventricular septal defects had one-vessel disease, had coronary blood flow velocity measured only in angiographically normal vessels, and did not undergo coronary angioplasty. Oral and written consent for the intra-aortic balloon evaluation was obtained from the patient and/or family before the study. The protocol was approved by the Human Subjects Committee of the Institutional Review Board. All clinically indicated medications were continued during the study period. Heparin was maintained to keep the activated clotting time >300 seconds.

Coronary arteriography was performed in a routine fashion using the femoral approach with standard 8F Judkins diagnostic catheters either after or before insertion of the intra-aortic balloon pump (Datascope, Inc.). Coronary angioplasty and/or thrombolytic therapy was performed as clinically indicated using standard procedures and equipment, including the Doppler angioplasty guide wire (vide infra). A stabilization period (15–20 minutes) of intra-aortic balloon pumping without repeat angioplasty or alteration of pharmacotherapy preceded data collection. There were eight other patients who remained hemodynamically unstable, required alteration of support drugs, or had a complicated or unsatisfactory angioplasty, which made measurement of coronary blood flow velocity unstable or unsuitable. These patients were excluded from the study. No patient had a complication as a result of coronary flow velocity measurements.

### Coronary Flow Velocity Measurements

**Doppler guide wire.** Subselective intracoronary flow velocity was measured with a 0.018-in. Doppler angioplasty guide wire (Flowwire, Cardiometrics, Inc., Mountain View, Calif.). As described by Doucette et al., the Doppler angioplasty guide wire is a 175-cm-long 0.018-in.-diameter flexible steerable guide wire with a 12-MHz piezoelectric ultrasound transducer integrated into the tip. The forward-directed ultrasound beam diverges in a 27° arc from the long axis (measured to the −6-decibel round-trip points of the ultrasound beam pattern). The pulse repetition frequency of >40 KHz, pulse duration of ±0.83 msec, and sampling delay of 6.5 msec is standard for clinical use. The system is coupled to a real-time spectrum analyzer, videocassette recorder, and video page printer. The quadrature/Doppler audio signals are processed by the spectrum analyzer using online fast Fourier transformation to provide a scrolling gray scale spectral display. The frequency response of the system calculates approximately 90 spectra per second. Simultaneous ECG and arterial pressures are also input to the video display. The Doppler guide wire velocity demonstrated excellent correlation with electromagnetic flow velocity and volumetric flow in straight and curved tubed models as well as in the in vivo testing using a circumflex canine coronary artery. The Doppler guide wire measures phasic flow velocity patterns and tracks linearly with flow rates in most small, straight coronary arteries.

### Table 1. Clinical Data for Patients Who Received an Intra-aortic Balloon Pump

<table>
<thead>
<tr>
<th>Patient</th>
<th>Age (years)</th>
<th>Sex</th>
<th>Condition/(indication)</th>
<th>CAD</th>
<th>LVEF (%)</th>
<th>Left ventricular WMA</th>
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<tr>
<td>1</td>
<td>57</td>
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<td>RCA</td>
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<td>IH</td>
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<table>
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<td>7A</td>
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<tr>
<td>5A</td>
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</table>

*A, angiographically normal artery in patient number above.

CAD, coronary artery under study; LVEF, left ventricular ejection fraction; WMA, left ventricular wall motion abnormality; IMI, inferior myocardial infarction; VF, fibrillation; CHF, congestive heart failure; BP, hypotension; AMI, anterior myocardial infarction; LV, left ventricle; UA, unstable angina; CABG, subsequent coronary artery bypass graft surgery (rescue, rescue coronary angioplasty); VT, ventricular tachycardia; VSD, ventricular septal defect; RCA, right coronary artery; LAD, left anterior descending coronary artery; Cx, circumflex coronary artery; D1, first large diagonal branch; OM, obtuse marginal artery; IH, inferior left ventricular hypokinesia; AD, anterior left ventricular dyskinesia; AH, anterior hypokinesia; ALH, anterolateral left ventricular hypokinesia; AA, anterior apical akinesia; IA, inferior akinesia.
Clinical Measurement Protocol

When possible, coronary artery flow velocity data proximal and distal to the critical stenoses were obtained before angioplasty (or coronary bypass surgery). After coronary angioplasty, data were obtained with the Doppler guide wire positioned distally and then again after guide wire withdrawal to a proximal, angiographically normal coronary arterial segment. Data in each location were obtained with and without intra-aortic balloon pumping (1–2 minutes after cessation of intra-aortic balloon pumping). Of the nine patients with flow velocity data measured before angioplasty, one patient had thrombolytic therapy with an 83% angiographic left anterior descending stenosis and did not have angioplasty but proceeded to elective bypass surgery for three-vessel coronary artery disease after flow velocity measurements during intra-aortic balloon pumping. Six patients had total coronary occlusion with no antegrade or retrograde flow (TIMI grade 0). In four patients, five angiographically normal arteries were selected as reference vessels for proximal and distal velocity measurement comparisons. The location and guide wire tip angle were maintained constant over each of the brief study periods. The Doppler signal was processed with the velocimeter (Cardiometrics, Inc.), from which mean and phasic velocity spectral signals (with fast Fourier transformation) were displayed and recorded on a standard 0.5-in. VHS recorder. Heart rate was measured from the ECG. Arterial pressures were measured with standard fluid-filled transducers (Namic, Inc., Glen Falls, N.Y.).

Translesional Pressure Gradients

Because of the critical presentation and total occlusion of the target vessel in some patients, translesional pressure gradients were not obtained before angioplasty. Nine patients had translesional (aortic-distal coronary) gradient measurements performed after angioplasty using a 2.2F tracking catheter (Target Therapeutics, Palo Alto, Calif.) and fluid-filled transducers. Hemodynamic data, comparing guiding catheter and coronary artery pressures at the proximal and distal guide wire locations, were recorded on the physiological recorder (VR-12 PPG, White Plains, N.Y.).

The intra-aortic balloon pump console (Datascope, Inc.) was set on automatic R wave deflation (mandatory deflation to within 40 msec of the R wave) with manual inflation adjustments to inflate the balloon at the diastolic notch of aortic pressure. Data were obtained before and during intra-aortic balloon pumping at cycles of 1:1 (intra-aortic balloon pump following every intrinsic beat). The intra-aortic balloon pump volume was set at 40 ml, the maximal balloon inflation volume for all subjects.

Coronary Velocity Signal Analysis

Coronary artery velocity signals were also recorded on thermal video printing paper at a paper speed of 50
mm/sec and digitized on an incorporated microcomputer system. The diastolic flow velocity integral (DFV,) was obtained by planimetry of the area under the diastolic velocity signal from the aortic dicrotic notch to the systolic pressure upstroke as previously reported.\(^{16}\) The mean flow velocity was computed from the digitized area of the total flow velocity integral. At least three basal, unaugmented beats were also measured and averaged for the baseline value used to compute the relative (percent) change from baseline. The coronary flow velocity variables were also reported as a percent of baseline value calculated as \([\text{DFV, augmented } - \text{DFV, base}] / \text{DFV, base}]\times100.\) The percent change from the proximal to distal location was similarly computed as \([\text{DFV, proximal } - \text{DFV, distal}] / \text{DFV, distal}]\times100.\)

Absolute coronary blood flow was estimated from the products of vessel cross-sectional area (assuming circular geometry), the diastolic flow velocity integral, and heart rate.\(^{17}\)

**Coronary Angiographic Measurements**

To assess changes in coronary artery dimensions and identify movement of the velocity guide wire that may produce signal artifact during intra-aortic balloon pumping, a left (or right) coronary cineangiogram was obtained in four patients with and without intra-aortic

![Figure 2](image-url)
balloon pumping. Coronary artery dimensions before and after angioplasty were measured from the developed cineangiographic films projected on a General Electric CAP-12 projector. Digital computer-assisted calipers (Sandhill Scientific, Inc., Littleton, Colo.) were used to measure the artery segment in the proximal segment and 5–10 mm distal to the guide wire tip. The 8F guiding catheter (2.67 mm) was used as a scale factor for absolute dimension calculations in millimeters used in the calculation of blood flow.

**Statistical Analysis**

Data were compared with Student's paired t test. A statistically significant difference is identified with p < 0.05. Data are presented as mean ± 1 SD unless otherwise indicated.

**Results**

**Study Population**

Coronary angioplasty was successful and uncomplicated without significant residual arterial narrowing (<40% diameter narrowing) in 11 of 12 patients (Table 1). One patient had elective bypass surgery after coronary angiography and distal coronary flow measurement. Four patients had emergency angioplasty within 12 hours after failed thrombolytic therapy and received intra-aortic balloon pumping per protocol. One patient (patient 5) had urgent angioplasty after acute recurrent ischemia 3 days after thrombolytic therapy while receiving intravenous heparin in the intensive care unit.

**Case Reports**

**Case 1.** A 73-year-old man (patient 7) with refractory and unstable angina, despite maximal medical therapy, had coronary angiography that demonstrated severe three-vessel coronary artery disease with total occlusion of the left anterior descending and right coronary arteries with an 89% narrowing of the proximal circumflex artery distal to a large and angiographically normal marginal branch (Figure 1, left panel). The left ventricular ejection fraction was 0.22 with anterior dyskinesis and severe inferior hypokinesis. After cardiothoracic surgical consultation, high-risk coronary angioplasty was performed with insertion of an intra-aortic balloon pump. Before angioplasty, coronary blood flow distal to the stenosis was <5 cm/sec and minimally affected by intra-aortic balloon pumping (Figure 1, right upper panel). After successful angioplasty, distal coronary mean flow velocity was >30 cm/sec and further augmented to >70 cm/sec with intra-aortic balloon pumping. Similar increases in mean flow velocity were also observed in the adjacent angiographically normal marginal branch vessel.

**Case 2.** A 63-year-old man (patient 5) with an acute, extensive inferior myocardial infarction 3 days before developing recurrent angina had coronary angiography that showed severe one-vessel disease with 88% narrowing of the large right coronary artery (TIMI grade flow 1) with only insignificant luminal irregularities of the contralateral vessels (Figure 2, left panels). The left ventricular ejection fraction was 48% with severe inferior hypokinesis. Intra-aortic balloon pump was inserted for unstable postinfarction angina with depressed left ventricular function. Before angioplasty, both proximal and distal coronary flow velocities were reduced and minimally augmented with intra-aortic balloon pumping (Figure 2, right panels). After successful angioplasty, there was significant improvement in proximal and distal blood flow velocities to >35 cm/sec with the intra-aortic balloon pump further augmenting flow to >50 cm/sec in the distal artery. Similar responses were measured in the contralateral left anterior descending reference artery.

**Case 3.** A 61-year-old man (patient 3) developed refractory angina pectoris with dyspnea 5 years after coronary artery saphenous vein bypass graft surgery. Coronary arteriography revealed total occlusion of grafts to the left anterior descending and circumflex coronary arteries with a patent graft to the right coronary artery. The native left anterior descending and proximal right coronary arteries were occluded. The circumflex artery was narrowed by 80% serial midcoronary artery stenoses (Figure 3, top panels). Left ventricular ejection fraction was 38% with extensive anterior and inferior akinesia and lateral wall hypokinesis. Because of the persistent angina and positive thallium scintigraphy in the lateral distribution, an elective, high-risk coronary angioplasty was undertaken with prophylactic placement of an intra-aortic balloon pump. Angioplasty was performed successfully without hemodynamic compromise, despite reversible ST segment changes. After angioplasty, a 15 mm Hg resting translesional gradient was then measured and correlated with changes in coronary blood flow velocity. During intra-aortic balloon pumping the distal diastolic flow velocity integral increased from 28 to 35 units, mean velocity from 45 to 54 cm/sec, and peak velocity from 61 to 84 cm/sec, despite a >25 mm Hg balloon pump-induced diastolic pressure gradient.

**Case 4.** A 75-year-old man (patient 9) with unstable angina after acute anterior myocardial infarction was treated with intravenous tissue-type plasminogen activator and had an intra-aortic balloon pump inserted.
before anticipated coronary angioplasty. Coronary angiography revealed significant narrowing in all three major vessels. The left ventricular ejection fraction was 0.45 with inferior and apical akinesis. The coronary blood flow velocity was measured in the left anterior descending artery prior to urgent coronary bypass surgery (Figure 4). In the distal arterial segment, mean and peak diastolic velocities were 17 and 27 cm/sec, respectively, which were augmented to 19 and 35 cm/sec during intra-aortic balloon pumping, respectively, despite an angiographic 85% diameter narrowing of the artery.

Coronary Flow Velocity Before Angioplasty

Because of the critical nature of the patients, some requiring urgent intervention, preangioplasty measurements could be obtained in only nine patients (Table 2). Before angioplasty, peak distal diastolic flow velocity was 5.3±9.6 cm/sec, nearly below the detectable level of the measurement system (<5 cm/sec). Six patients (patients 1, 2, 4, 8, 12, and 13) had total occlusions with zero distal flow before intervention. The guide wire passage through total occlusions did not significantly improve flow. Intra-aortic balloon pumping did not significantly augment distal flow velocity in these patients.

Coronary Flow Velocity After Angioplasty

After angioplasty, distal coronary diastolic velocity integral and peak and mean flow velocities increased (13.3±8.4 units, 36.4±18.3 and 24.0±11.4 cm/sec, respectively; all p<0.01 versus before angioplasty) (Tables 2 and 3). With intra-aortic balloon pumping, distal diastolic velocity integral and peak and mean flow velocities were further increased 38±39%, 53±18%, and 23±16%, respectively (all p<0.01 versus basal flow after angioplasty) (Figure 5). The systolic velocity integral and peak velocity were minimally augmented during intra-aortic balloon pumping (10±59% and 3±33%, respectively; both p<0.05). Relative to the proximal location, intra-aortic balloon pumping increased distal coronary artery diastolic velocity integral and peak and mean flow velocities 69±87%, 83±83%, and 74±83%, respectively (all p<0.01 versus proximal). All proximal values were significantly higher than distal flow values with the exception of the systolic flow velocity during intra-aortic balloon pumping (Table 2).

In the five normal reference arteries, intra-aortic balloon pumping increased diastolic flow velocity integral and peak and mean velocities 49±17%, 49±33%, and 38±20%, respectively, in the proximal segments and 48±29%, 38±18%, and 20±6%, respectively, in the distal segments, which are values similar to those measured in the postangioplasty arteries (Table 3).

Intra-aortic balloon pumping increased calculated volumetric coronary blood flow from 104±68 to 138±87 ml/min and from 160±59 to 236±84 ml/min (both p<0.001) in the proximal segments of the atherosclerotic and normal reference arteries, respectively, and from 75±50 to 110±90 ml/min and from 98±33 to 142±39 ml/min (both p<0.05) in the distal atherosclerotic and normal vessel segments, respectively (Table 4).

Hemodynamic Data

Intra-aortic balloon pumping increased proximal and distal diastolic pressures 82±35% and 42±15%, respec-

tively (p<0.05) and reduced systolic pressure −10±5% and −7±7% (p=NS) (Table 5). During intra-aortic balloon pumping, diastolic augmentation of the distal pressure was lower than proximal artery pressures (111±27 versus 87±18 mm Hg, p<0.05). Heart rates were unaffected by intra-aortic balloon pumping. Minimal translesional coronary pressure gradients (≤15 mm Hg) were present after angioplasty at baseline. Intra-aortic balloon pumping produced small diastolic translesional gradients in patients 2–8.

Discussion

Although intra-aortic balloon pumping augments proximal coronary flow velocity, its effects on distal coronary blood flow or myocardial perfusion have generally been demonstrated to be minimal or absent,10,16 depending on the experimental animal preparation and clinical setting in which these data were obtained. The current study indicates that little or no coronary flow is detected in the epicardial artery distal to significant stenoses despite augmented diastolic pressure during intra-aortic balloon pumping. As shown by Segal et al15 and with the present study, after relief of vessel occlusion or severe coronary stenosis by angioplasty, both proximal and, more important, distal coronary blood flow velocity is increased. Blood flow velocity was further augmented by intra-aortic balloon pumping. The augmentation of flow was appreciated beyond the affected lesion, at least down to the distal two thirds of the major epicardial vessel under study. As case illustrated, the increase in flow velocity occurred despite a small but identifiable loss of perfusion pressure from the proximal coronary supply; as shown in cases 1 and 2, the loss was similar to that observed in normal ipsilateral and contralateral reference vessels. These data provide the first example of the influence of intra-aortic balloon pumping on directly measured proximal and distal coronary blood flow responses in humans after angioplasty and demonstrate the potential for augmenting myocardial perfusion when obstructive atherosclerotic lesions are suitably minimized.

Clinical Studies

These findings suggest previous studies of the use of intra-aortic balloon pumping in patients with acute myocardial infarction and cardiogenic shock in whom the initially favorable results are ultimately overshadowed by delayed high mortality rates in excess of 80%.20,21 The limited distal flow velocity and failure to increase flow beyond most critical coronary stenoses demonstrated here indicate that the mechanism of intra-aortic balloon pumping benefit in such patients occurs predominantly through afterload reduction more than augmented coronary blood flow. However, in similar patients in the thrombolytic/angioplasty era, reduced mortality rates are reported.20,21 The present study demonstrates that distal coronary flow can be substantially increased with angioplasty and further augmented with intra-aortic balloon pumping, a phenomenon that may be associated with a higher rate of artery patency, flow restoration, and improved patient survival. Intra-aortic balloon pumping may also be associated with augmented distal flow velocity in some patients after thrombolysis for acute myocardial infarction, such as demonstrated in case 4.
Other investigators have demonstrated similar increases in coronary blood flow velocity using an electromagnetic flowmeter in vein bypass grafts at coronary artery surgery and in proximal vessel segments with transesophageal echocardiography in stable patients. However, most experimental studies reporting little or no change in coronary blood flow used several different and indirect coronary blood flow measurement techniques. The present study confirms prior observations that blood flow (velocity) directly measured in...
The proximal vessel increases in nearly all patients and differs from our earlier investigations by using spectral Doppler signal analysis and distal subselective velocity measurement with Doppler guide wire methodology.

The critical question of whether a 25% augmentation of distal mean coronary flow by intra-aortic balloon pumping provides substantial clinical benefit cannot be answered from this study. However, in most cases, this modest increase in distal velocity is accompanied by a shift in the phasic relation of flow with a decrement or no increase in systolic flow and a significant increase in diastolic flow. Previous studies have demonstrated that subendocardial perfusion occurs during diastolic epicardial coronary flow and that the systolic component provides little contribution to subendocardial perfusion. Therefore, by shifting flow to diastole, the physiological benefit of increased flow may be more dramatic than can be inferred from a 25% increase in mean flow. In addition, the clinical significance of enhanced coronary blood flow may be most evident in the setting of acute ischemic syndromes where low-flow states may predispose to recurrent thrombotic occlusion. This phenomenon may be active in patients who had coronary angioplasty after failed thrombolytic reperfusion and demonstrated a reduced incidence of postprocedural abrupt closure when intra-aortic balloon pumping was used as adjunctive therapy.12,13

Study Limitations

The net hemodynamic effects of intra-aortic balloon pumping depend on a wide variety of variables (e.g., volume of the balloon, relative balloon/aorta size ratio),1−3 which cannot be controlled among patients. Because each patient served as his or her own control, the relative changes from baseline can be compared. The intensive pharmacotherapy (intravenous vasopressors, inotropes, and vasodilators) was a potentially confounding but unavoidable clinical variable. Patient safety precluded cessation or modification of pharmacotherapy during the course of the study. However, the stabilization period within the catheterization laboratory was considered satisfactory to achieve a relatively steady state.

The limitations of intracoronary Doppler catheter techniques are well described.22,23 Flow velocity measurements do not provide an absolute value but are linearly related to changes in absolute flow when vessel area remains constant.22 Given the unchanged diameter of the proximal coronary vessel during balloon pumping observed in an earlier study,11 the flow velocity signal

**TABLE 2.** Coronary Blood Flow Velocity Data

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<tr>
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<th>Intra-aortic balloon pumping</th>
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</tbody>
</table>

D1, diastolic flow velocity integral (units); S1, systolic flow velocity integral (units); D1, peak diastolic velocity (cm/sec); S1, peak systolic velocity (cm/sec); %Δ, percent change proximal versus distal values; MV, mean velocity (cm/sec).

†p<0.05 proximal vs. distal.

‡p<0.01 vs. intra-aortic balloon pumping off.

**TABLE 3.** Percent Change During Intra-aortic Balloon Pump Counterpulsation

<table>
<thead>
<tr>
<th></th>
<th>%ΔD1</th>
<th>%ΔS1</th>
<th>%ΔD1</th>
<th>%ΔS1</th>
<th>%ΔMV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atherosclerotic artery after angioplasty</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proximal</td>
<td>36±15</td>
<td>−16±23*</td>
<td>51±25</td>
<td>−15±21*</td>
<td>29±20</td>
</tr>
<tr>
<td>Distal</td>
<td>36±37</td>
<td>10±59</td>
<td>54±49</td>
<td>3±33</td>
<td>26±17</td>
</tr>
<tr>
<td>Normal reference artery</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proximal</td>
<td>49±17</td>
<td>−4±33</td>
<td>49±33</td>
<td>−5±21</td>
<td>38±20</td>
</tr>
<tr>
<td>Distal</td>
<td>48±29</td>
<td>−17±19</td>
<td>38±18</td>
<td>−22±17</td>
<td>20±6</td>
</tr>
</tbody>
</table>

D1, diastolic flow velocity integral (units); S1, systolic flow velocity integral (units); D1, peak diastolic velocity (cm/sec); S1, peak systolic velocity (cm/sec); %Δ, percent change.

*p<0.05 proximal vs. distal.
can thus be used to indicate important volumetric alterations from baseline conditions. Compared with the preangioplasty dimensions, the diameter of the distal vessel after angioplasty often enlarges due, in part, to flow-mediated vasodilation. An enlarged vessel cross-sectional area with an increased flow velocity integral strongly supports the increased volumetric as well as relative flow velocity augmentation. Doppler velocity signal artifact could have been produced by movement of the guide wire tip with a changing angle of the Doppler beam relative to the axis of the blood flow. A relatively stationary placement of the Doppler guide wire was observed in all patients. Proximal catheter motion artifact has been excluded in prior similar studies.¹¹ The Doppler guide wire was successful as a primary guide wire in 80% of attempts with a satisfactory velocity signal obtained in 90% of patients.

Although the Doppler guide wire technique can detect collateral flow velocity,²⁴-²⁶ only one patient had angiographic collaterals to the instrumented study vessels with a >50% augmentation of the small retrograde diastolic flow velocity integral. The effects of intra-aortic balloon pumping on collateral flow remain to be determined in a larger patient group.

Conclusions

Intra-aortic balloon pumping has minimal effect on coronary blood flow beyond most critical stenoses and unequivocally increases coronary blood flow velocity in the distal coronary artery in patients after successful angioplasty. These findings suggest that patients with ischemia due to severe coronary obstructions obtain benefit more by intra-aortic balloon pump–mediated

TABLE 4. Angiographic Data on Lesions, TIMI Grade, and Coronary Blood Flow

<table>
<thead>
<tr>
<th>Patient</th>
<th>Age (years)</th>
<th>Sex</th>
<th>Before</th>
<th>After</th>
<th>TIMI flow grade</th>
<th>Coronary blood flow</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Proximal</td>
<td>Distal</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>IABP off</td>
<td>IABP on</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>IABP off</td>
<td>IABP on</td>
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<td>28</td>
<td>2</td>
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<tr>
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<tr>
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<td>3</td>
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<tr>
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<td>51.1</td>
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<td>73</td>
<td>Female</td>
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<td>10</td>
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</table>

Mean±SD

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<tr>
<th>Reference arteries</th>
<th>95±7</th>
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<tr>
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<td>141.9</td>
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<td>15</td>
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<td>196.0</td>
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<tr>
<td>5A</td>
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<td>381.8</td>
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</tbody>
</table>

Mean±SD

| 160±50 | 236±84* |
| 98±33  | 142±39* |

TIMI, Thrombolysis in Myocardial Infarction flow grade (0–1, none or slow; 2, moderate filling; 3, normal flow); IABP, intra-aortic balloon pumping.

Coronary blood flow (ml/min) calculated from diastolic flow velocity integrals multiplied by vessel cross-sectional area multiplied by heart rate.¹⁷

*P<0.01 vs. IABP off.
†P<0.01 vs. reference artery.
‡Collaterally supplied.
§A, angiographically normal artery in patient number above.
TABLE 5. Hemodynamic Data

<table>
<thead>
<tr>
<th>Patient</th>
<th>Systolic Off</th>
<th>Diastolic Off</th>
<th>Systolic On</th>
<th>Diastolic On</th>
<th>A-C gradient</th>
<th>Heart rate (bpm)</th>
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</thead>
<tbody>
<tr>
<td>1</td>
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<td>70</td>
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<td>62</td>
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<td>3</td>
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<td>50</td>
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<tr>
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<td>86</td>
<td>121</td>
<td>86</td>
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<td>90±19</td>
</tr>
</tbody>
</table>

Mean±SD 109±21 71±21 98±19 61±13 111±27 97±10 66±6 90±81 63±13 87±18 8±6 27±1

A-C gradient, aortocoronary translesional pressure gradient at rest (off) and during intra-aortic balloon pumping (on) (mm Hg); augmented, augmented diastolic pressure (mm Hg); diastolic, diastolic pressure (mm Hg); off, basal values; on, augmented values; systolic, systolic pressure (mm Hg).

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