Table I. Angiographic and hemodynamic data

		LMCA diameter (mm)		*Aortic*		*Intracoronary*	
Patient No.	*Age (yr)*	*Ostium*	*Mid-LMCA*	*Syst.*	*Diast.*	*Syst.*	*Diast.*
1	67	2.1	5.1	140	53	118	40
2	67	2.5	4.6	156	84	103	44
3	53	1.9	4.5	138	68	98	40
4	53	1.9	3.8	126	78	102	46
5	62		2.9	145	83	90	43
6	72		2.4	130	55	105	42
7	59		1.9	163	86	110	43
8	66		3.0	136	72	104	40
9	63		1.9	160	78	108	44
10	60		2.3	132	70	106	38
11	75		1.9	157	70	79	25
12	65		2.3	176	78	82	25
13	58		1.9	135	67	120	55
14	63		1.9	105	85	93	64
15	67		3.0	167	60	150	47
16	63		2.2	145	66	120	60
17	65		2.1	122	60	108	52
18	65		2.1	152	72	143	63
19	65		2.4	165	82	156	68
20	57		3.0	145	84	80	24
Mean	63	2.1	2.3	145	72	109	45
SD	6	0.3	0.4	18	10	21	13
No.	20	4	16	20	20	20	20

All patients were men with the exception of patient no. 13. Patients no. 1 through 4 had ostial left main stenosis. Patients no. 5 through 20 had stenosis of the entire length of the left main coronary artery.
Diast., Diastolic pressure (mm Hg); LMCA, left main coronary artery; Syst., systolic pressure (mm Hg).

20 patients. There were 19 men and 1 woman, aged 57 to 72 years (mean ± SD, 63 ± 6 years). The indication for coronary angiography was stable angina in 11 patients, unstable angina in four patients, recent myocardial infarction in three patients, congestive heart failure in one patient, and previous coronary artery bypass surgery in one patient. All patients were studied by the femoral approach. An 8F left Judkins catheter (Cordis Corp., Miami, Fla.) was used in 18 patients and an 8F left Amplatz catheter (Cordis Corp.) was used in two. The ventricularized pressures were recorded after left ventricular angiography but usually before injecting the radiographic contrast medium into the left coronary artery.

The diameter of the left main coronary artery was measured with a vernier caliper with digital readout. The actual coronary artery diameter was obtained after correction for the magnification of the angiographic image. The diameter of the tip of the catheter and a 1 × 1 cm grid exposed at the mid-chest were used as a reference. The left coronary angiogram was inspected for the degree of reflux of the contrast material from the left main coronary artery to the aorta.

Dog experiments. Three male closed-chest mongrel dogs were anesthetized with pentobarbital and were artificially ventilated. An 8F left Amplatz guiding catheter was positioned at the ostium of the left main coronary artery. A 3.5F 20 mm angioplasty catheter was advanced into the circumflex artery. Pressures from the tip of the angioplasty catheter were recorded at various degrees of balloon inflation. Contrast material was injected periodically via the guiding catheter to detect the degree of occlusion of the coronary artery by the balloon. In one experiment, instead of the angioplasty catheter a 5F Swan-Ganz catheter (Baxter Healthcare Corp., Edwards Division, Santa Ana, Calif.) was advanced into the left main coronary artery. The pressures recorded through the Swan-Ganz catheter had less distortion of the waveform than those obtained with the smaller angioplasty catheter.

RESULTS

All patients had substantial narrowing of the left main coronary artery (Table I). In 16 patients, the entire length of the left main artery was stenosed. The mean diameter of the residual lumen was 2.3 ± 0.4 mm. This is only slightly larger than the diameter of the tip of the 8F Judkins catheter, which measures 1.9 mm. In the remaining four patients, only the ostium of the left main coronary artery was stenosed. The mean diameter of the ostium was 2.1 ± 0.3 mm, and the mean diameter of the normally appearing body of the left main coronary artery was 4.5 ± 0.5 mm. The latter measurement is comparable to the expected normal diameter of a left main

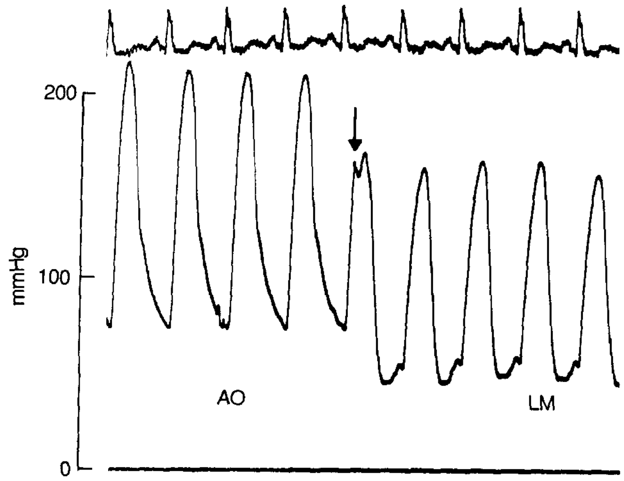

Fig. 1. A sudden change in the pressure waveform morphology as the 8F left Judkins catheter is advanced from the aorta (*AO*) into a stenosed left main coronary artery (*LM*). *Arrow* indicates the point of the instant change to the ventricularized waveform.

coronary artery in men, which MacAlpin et al.[1] found to be 4.3 ± 0.6 mm and Vieweg et al.[2] reported to be 4.6 ± 0.2 mm.

On flouroscopy, 10 of 20 patients had calcification in the region of the left main coronary artery. The assessment of the degree of reflux of the contrast material into the aorta upon its injection into the left main artery revealed no reflux in five, a trace in 10, and a normal amount in five patients. When present, the reflux was frequently in the shape of a narrow jet, which suggested that the contrast material was being expelled through a very small residual space between the wall of the left main artery and the catheter.

The advancement of the angiography catheter into the left main coronary artery resulted in a sudden change in the pressure waveform, which differed from the aortic pressure in three ways (Fig. 1). First, the rate of the pressure rise was slightly slower in this waveform than it was in the aortic tracing. Second, the dicrotic notch was absent; the pressure continued to fall rapidly until the diastolic nadir was reached. Third, a distinct presystolic positive deflection was inscribed before the beginning of the systolic pressure rise. Fig. 2, recorded in a patient with left main stenosis and variable atrioventricular conduction, demonstrates that this positive deflection is consistently related to atrial contraction.

In addition to the changes in the waveform, the levels of the systolic and diastolic pressures recorded from the left main coronary artery were always lower than those in the aorta (Fig. 3 and Table I). The magnitude of the decrease in the systolic pressure was variable; it ranged between 9 and 94 mm Hg. This represents a 5% to 53% decrease from the aortic pressure. The decrease in the diastolic pressure was also variable. It ranged between 6 and 60 mm, which represents a 5% to 71% decrease from the aortic pressure. In 10 of 20 patients the diastolic intracoronary pressure clustered around 42 mm Hg.

The inflation of a balloon catheter in the left main or the circumflex artery of a dog resulted in changes of the pressure waveform that were quite similar to those observed in the tracings recorded in patients with left main stenosis. The decrease in the rate of systolic pressure rise, the rapid decline of pressure in diastole, and the presystolic positive wave were evident (Fig. 4). However, this waveform was detected only if the occlusion of the artery was incomplete. Thus the ventricularized pressure represents a waveform that is intermediate between the aortic pressure and the coronary wedge pressure (Fig. 5).

When the balloon was inflated very slowly, we observed a series of waveforms that were characterized by progressive decreases in the systolic and diastolic pressures (Fig. 6). Flow in the coronary artery, as determined by injection of the contrast medium under fluoroscopy, was maintained until the time of appearance of the coronary wedge pressure. At that time, the coronary artery was completely occluded by the balloon.

DISCUSSION

Several clinical investigators have commented on the sudden change in pressure in the course of catheterization of stenosed left main coronary arteries.[3-5] In the literature, this event has been referred to as ventricularization, pressure drop, or damping of pressure. The characteristic features of this pressure change and its mechanisms have not been investigated. The description of ventricularization in the textbooks of cardiac catheterization is incomplete.[6,7]

The term "ventricularization" is actually a misnomer. The pressure waveform that is recorded from a stenosed left main coronary artery does resemble the left ventricular pressure waveform to some degree, but this is simply a coincidence. Our experiments show that the "ventricularized" coronary pressure has no etiologic relationship to the left ventricular pressure. Rather, it is related to the aortic pressure that is altered during its transmission through the very small residual space between the catheter and the stenosed coronary artery.

The changes observed upon advancing a catheter into the ostium of a stenosed coronary artery can be divided into the changes in the pressure waveform and the changes in the height of the systolic and diastolic pressures. The most striking feature of the

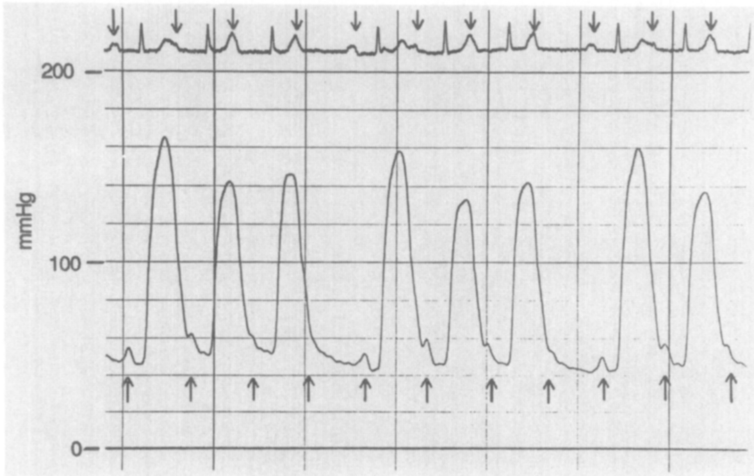

Fig. 2. Intracoronary pressure recorded in a patient with a left main coronary stenosis and a 4:3 Wenckebach atrioventricular block. The locations of the P waves and the corresponding waveforms are indicated by the *arrows*.

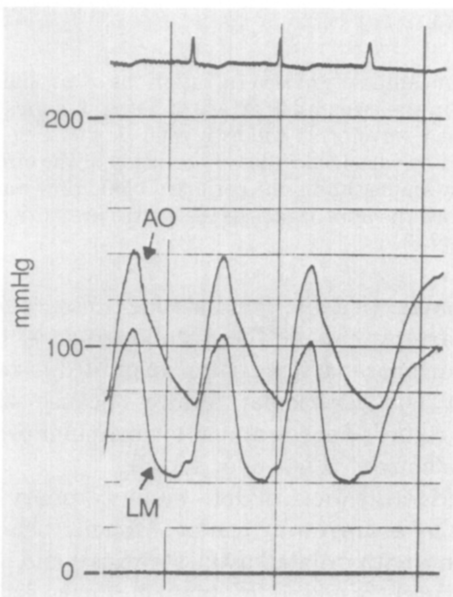

Fig. 3. Simultaneous pressures in a patient with left main coronary artery stenosis recorded with an 8F pigtail catheter positioned in the ascending aorta (*AO*) and with an 8F left Judkins catheter positioned in the left main coronary artery (*LM*).

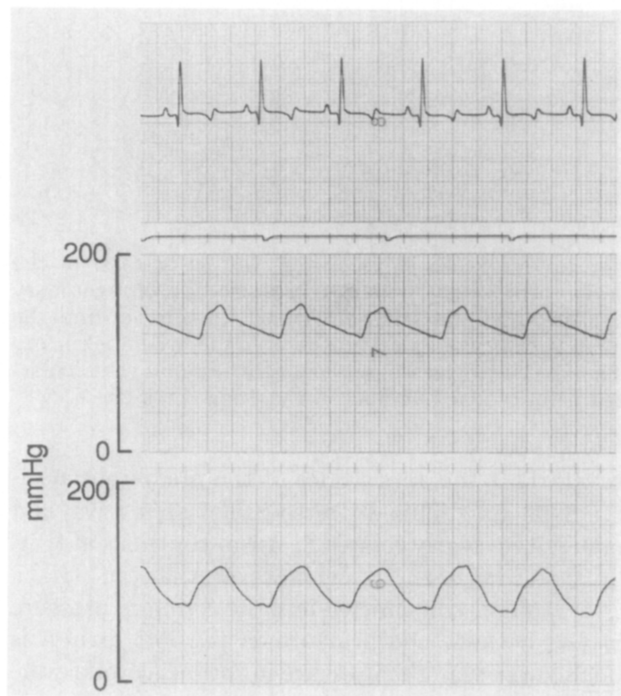

Fig. 4. The electrocardiogram (*top panel*), the carotid arterial pressure (*middle panel*), and the intracoronary pressure (*bottom panel*) recorded in a dog after partial inflation of a 5F Swan-Ganz catheter in the left main coronary artery. The intracoronary waveform has a ventricularized appearance.

ventricularized waveform is the steep decline of the pressure in diastole. Similar waveforms have been observed in patients with stenoses of both pulmonary arteries and in patients with supravalvular aortic stenosis.[8-10] The mechanism for the rapid decline of the descending limb of the pressure curve in all these clinical situations is probably the same. The stenotic lesion restricts the diastolic blood flow into the vessel from which the pressure is being recorded—the vessel being the left coronary artery in the case of left main stenosis.

In addition to the rapid decline of the pressure in diastole, the other characteristic feature of this

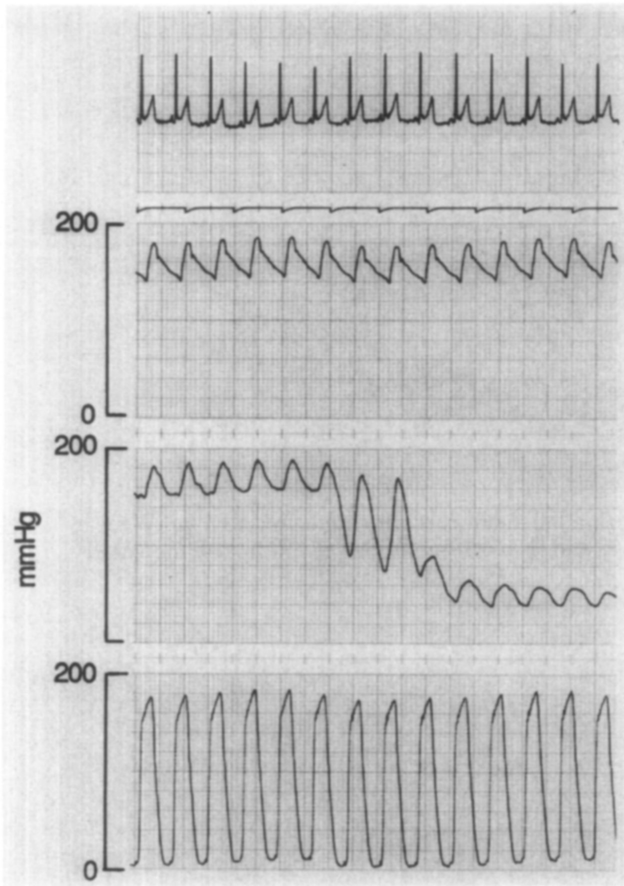

Fig. 5. A continuous recording (*top to bottom*) of the electrocardiogram, the aortic pressure, the intracoronary pressure, and the left ventricular pressure during the inflation of an angioplasty catheter in the circumflex artery of a dog. The intracoronary pressure becomes ventricularized before the appearance of the wedge pressure.

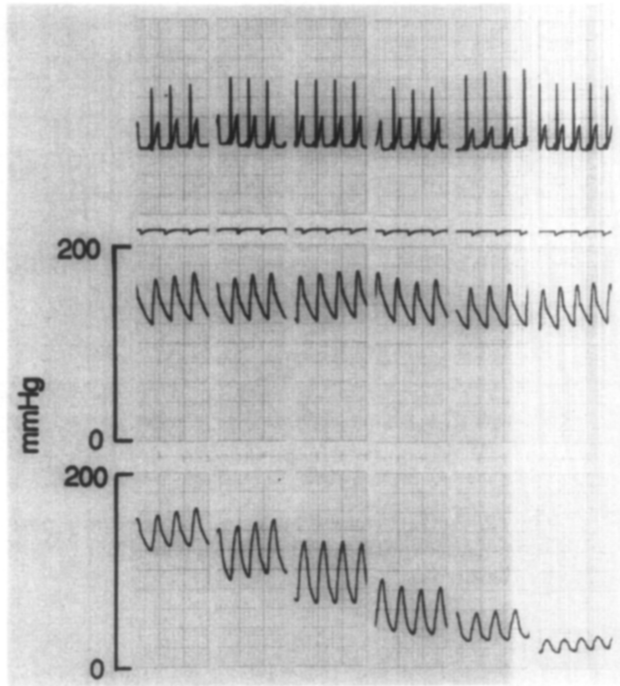

Fig. 6. A composite of several inflations of an angioplasty catheter in the circumflex artery of a dog. A series of ventricularized waveforms (*bottom row, panels 2 to 5*) was generated by various degrees of occlusion of the circumflex artery. By angiography, the coronary blood flow was maintained until the appearance of the wedge pressure (*bottom row, panel 6*).

waveform is the appearance of the presystolic positive deflection. This wave resembles an a wave, and indeed it is clearly related to atrial contraction (Fig. 2). It does not seem likely, however, that the atrial a wave could be transmitted into the coronary pressure tracing because the pressure in the left atrium is much lower than the pressure in the left coronary artery. We believe that this waveform, which is inconspicuous but present in recordings of normal ascending aortic pressures, is generated by the motion of the ascending aorta during atrial systole. This motion artifact is simply easier to identify in the presence of left main stenosis because in these patients the slope of the intracoronary pressure is flat at the time of the appearance of this wave.

The degree of pressure drop between the ascending aorta and the stenosed left main coronary artery was variable. Usually, the diastolic pressure fell to a greater extent than did the systolic pressure. The fall in the intracoronary pressure was not due to acute ischemic left ventricular failure because simultaneously recorded aortic and left ventricular pressures were unchanged (Figs. 3, 5, and 6).

The identification of left main coronary artery stenosis by angiography can be difficult. This is true in patients with isolated ostial stenosis[11] and in those with diffusely diseased left main coronary arteries.[12] The severity of the latter lesion is particularly difficult to ascertain when both the proximal left anterior descending artery and the proximal circumflex artery are diseased.[13] We found that the presence of an ostial lesion or a diffusely stenosed left main coronary artery can be anticipated by the recognition of the described pressure waveform even before contrast medium is injected into the coronary artery. When ventricularization is observed, the angiographer should carry out the study with the minimum of appropriate views and with an increased awareness of the potential for serious complications. Gordon et al.[14] found that the distance from the catheter tip to

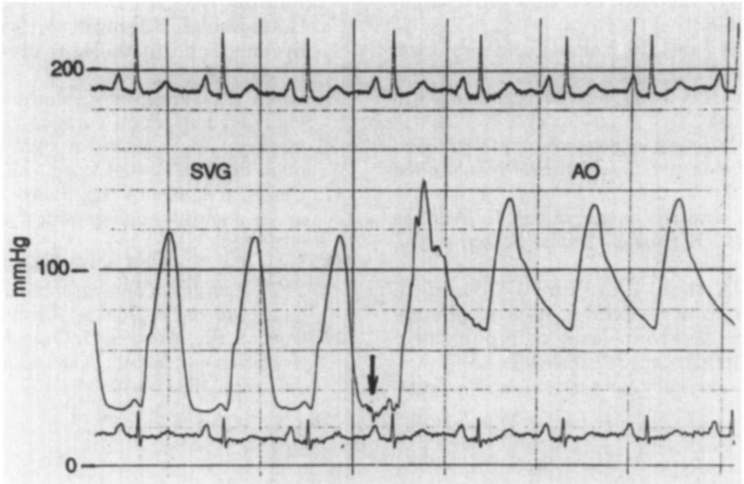

Fig. 7. Ventricularization of pressure during the cannulation of a saphenous vein graft (*SVG*) that had a high-grade stenosis at the site of its proximal anastomosis. The vein graft supplied a large obtuse marginal artery that was completely occluded at its origin from the circumflex artery. *Arrow* identifies the time of pullback from the vein graft to the ascending aorta (*AO*).

a left main coronary lesion was related to complications of cardiac catheterization.

We believe that the recognition of ventricularization contributes to improving the safety of coronary angiography in patients with left main coronary stenosis. In such patients, it would seem prudent to use a nonionic contrast medium, to select the minimum (one to three) views to define the left main disease and any other lesions, and to avoid repeated entry of the catheter into the diseased left main coronary artery that could result in dissection and thrombosis. One of the patients reported herein (patient No. 20) developed refractory hypotension after the first injection of the contrast medium into the left coronary artery. At autopsy, the left main coronary artery was severely narrowed by atherosclerosis and thrombosis. Some angiographers recommend that nonselective injection of the contrast medium into the coronary cusp be done to identify the presence of left main coronary artery disease in order to avoid the potentially fatal injury of the left main coronary artery by the catheter. However, we have not been successful in obtaining sufficient opacification of the left coronary artery by the nonselective technique, and thus we do not find this step to be helpful. Because the ostium is usually best visualized in a shallow left anterior oblique projection, we recommend that the artery be first opacified in this view.

It should be emphasized that ventricularization can be seen in conditions ofther than left main coronary stenosis. Ventricularization will occur whenever the diameter of the coronary artery is similar to the diameter of the catheter entering the artery. In patients with left main coronary artery disease, a close match between the catheter and the artery indicates significant stenosis, since the diameter of the normal left main coronary artery should be approximately twice the diameter of the 8F Judkins catheter. We have observed ventricularization in a patient with a normal left main coronary artery in whom the catheter was unintentionally advanced into a stenosed circumflex artery, in patients with normal but small right coronary arteries, and in patients with proximally stenosed vein grafts (Fig. 7). However, the appearance of ventricularization upon catheterization of the left main coronary artery in most instances indicates the presence of severe left main coronary artery stenosis. The concept[7] that this waveform can be generated by an unfavorable position of the tip of the catheter against the arterial wall is not supported by our data. The appearance of ventricularization is an important clue to the presence of left main coronary artery stenosis, and its recognition should contribute to improving the safety of coronary angiography in patients with this disease.

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