Title

Failure of angiography to accurately depict the extent of coronary artery narrowing in three fatal cases of percutaneous transluminal coronary angioplasty

Journal

Journal of the American College of Cardiology, 19(6)

ISSN

0735-1097

Authors

Dietz, William A
Tobis, Jonathan M
Isner, Jeffrey M

Publication Date

1992-05-01

DOI

10.1016/0735-1097(92)90333-i

JACC Vol. 19, No. 6
May 1992:1261–70

MORPHOLOGIC STUDIES

Failure of Angiography to Accurately Depict the Extent of Coronary Artery Narrowing in Three Fatal Cases of Percutaneous Transluminal Coronary Angioplasty

WILLIAM A. DIETZ, MD, JONATHAN M. TOBIS, MD, FACC,* JEFFREY M. ISNER, MD, FACC
Boston, Massachusetts and Irvine, California

The angiographic and pathologic findings are described in three patients who died <24 h after failed percutaneous transluminal coronary angioplasty. In two of the three patients, coronary angiography performed before angioplasty disclosed apparently focal lesions in the left anterior descending and right coronary arteries. In these two patients quantitative angiographic analysis disclosed a minimal lumen cross-sectional area of 1.82 and 0.47 mm², respectively, at the sites of apparently focal stenoses before angioplasty; corresponding percent lumen area narrowing measured 84% and 91%, respectively, by quantitative angiography at these two sites.

In the third patient, coronary angioplasty was undertaken when the patient developed spontaneous occlusion of the right coronary artery several hours after diagnostic angiography. Retrospective quantitative angiographic analysis of the right coronary artery revealed a minimal lumen cross-sectional area of 1.14 mm², with 85% lumen area narrowing at the site of subsequent total occlusion and angioplasty.

In each of these three patients, necropsy examination disclosed that the distribution of coronary narrowing in the artery treated by angioplasty was in fact not focal; rather, in each of these three patients, the artery treated by angioplasty, as well as the extramural coronary arteries not treated by angioplasty, were severely narrowed by diffusely distributed atherosclerotic plaque. The angiographic and necropsy findings in these three patients document that coronary narrowing that remains occult by virtue of diffuse distribution may complicate evaluation of patients being considered for coronary angioplasty.

(J Am Coll Cardiol 1992;19:1261–70)

Although certain limitations of coronary angiography have been repeatedly documented by pathologic (1–9) and physiologic (10–13) studies, modifications involving instrumentation and analysis have been considered to obviate many of these previously established liabilities. Certain liabilities, however, remain unsolved. Chief among these is the pathoanatomic finding of diffuse, severe coronary artery narrowing. Diffusely diseased arteries have been demonstrated at necropsy (14–17) and are recognized to constitute a pitfall of diagnostic angiography (18); such diffuse, severe narrowing has less frequently been documented or even considered in patients undergoing percutaneous transluminal coronary angioplasty in whom angiographic evidence of focal narrowing represents the essential criterion for nonsurgical therapy.

The three patients described in this report document the extent to which diffuse coronary narrowing continues to pose a liability for angiographic analysis, including quantitative analysis of images recorded in multiple orthogonal obliquities. In particular, these three cases illustrate the extent to which this liability may compromise attempts to perform percutaneous coronary artery revascularization.

Methods

Clinical data. Coronary angiography and coronary angioplasty were performed on three patients at two institutions with standard diagnostic and interventional techniques. The clinical history was obtained retrospectively from medical records, catheterization records and reports of pathologic examination.

Angiographic analysis. Selective representative end-diastolic frames of coronary arteriograms were analyzed in at least two orthogonal views. Cine frames were digitally acquired onto computer memory by using a cine video camera mounted on a standard cine projector (Tagarno). Digitally acquired images were then quantitatively analyzed with use of a previously validated commercially available edge-detection computer-assisted software program (ImageComm). Calibration was performed by using the known dimensions of the angiographic catheter. Standard gray scales were employed. Absolute artery dimensions (lumen diameter and cross-sectional area) were determined for sites

From the Departments of Medicine (Cardiology), Pathology and Biomedical Research, St. Elizabeth's Hospital, Tufts University School of Medicine, Boston, Massachusetts and *the Department of Medicine (Cardiology), University of California at Irvine, California. This study was supported in part by Grant HL-40518 from the National Heart, Lung, and Blood Institute, National Institutes of Health, Bethesda, Maryland, and the John and Cora Davis Foundation, Washington, D.C.

Manuscript received July 23, 1991; revised manuscript received October 30, 1991, accepted November 19, 1991.

Address for reprints: Jeffrey M. Isner, MD, St. Elizabeth's Hospital, 736 Cambridge Street, Boston, Massachusetts 02135.

0735-1097/92/$5.00

of both maximal stenosis and reference segments (segments with angiographically normal appearance adjacent to sites of maximal stenosis). Percent stenosis was calculated as the difference between the lumen cross-sectional area of the reference segment and the stenotic segment, divided by the lumen cross-sectional area of the reference segment.

Pathologic examination. At necropsy, the epicardial coronary arteries were excised intact and serially cross-sectioned at 5-mm intervals. In Patient 3, this procedure was performed after the coronary arteries had been selectively cannulated and perfused with 10% buffered formalin at a mean pressure of 80 mm Hg. In the remaining two cases the coronary arteries were examined without pressure perfusion fixation. Each 5-mm section was inspected grossly for percent cross-sectional area narrowing and the presence of intracoronary thrombus, and these findings were recorded. The 5-mm sections were then prepared for light microscopic examination as described previously (19). Briefly, each coronary artery was decalcified in a solution of 10% formic acid and formalin if necessary, and fixed overnight in 10% buffered formalin. Segments were then dehydrated in graded alcohols, cleared with xylene, impregnated with and embedded in paraffin, and sectioned into 4-μm thick sections.

Sections stained with Verhoeff's elastic tissue stain as well as sections stained with hematoxylin-eosin were prepared from each 5-mm segment. The elastic-tissue-stained sections prepared from the coronary arteries of each patient were then inspected by light microscopy. Lumen cross-sectional area narrowing was calculated by positioning elastic-stained sections on the stage of a projection-light microscope. The image was then magnified 25 times onto a piece of opaque white paper and pencil tracings were made of the section's original lumen, denoted by the black-staining internal elastic membrane and the inner lumen, demarcated by the internal perimeter of the atherosclerotic plaque. Measurements of lumen area and native arterial area were performed by on-line computer analysis with commercially available computer software and hardware (Summasketch-MacMeasure, Apple Computer). Percent cross-sectional area narrowing was calculated by using the measured and original lumen areas.

Case Reports

Patient 1

A 54-year old man had a history of stable exertional angina for 8 years. One month before admission, he developed a crescendo anginal pattern, with angina occurring up to 3 times/day with minimal exertion. Elective coronary angiography performed 2 weeks before admission revealed a left dominant coronary circulation, focal stenosis of the proximal left anterior descending coronary artery (Fig. 1, a and b), and no focal narrowing of the remaining vessels.

Coronary angioplasty and emergency coronary bypass surgery. The patient was readmitted for elective coronary angioplasty of the left anterior descending coronary artery. A 0.014-in. (0.036-cm) guide wire was advanced easily beyond the proximal stenosis into the distal left anterior descending artery. However, the angioplasty catheter could not be advanced across the high grade stenosis, and ventricular tachycardia developed. The arrhythmia was treated successfully with a precordial thump and intravenous lidocaine, but hypotension required insertion of an intraaortic balloon pump. Despite these interventions, hypotension persisted in association with bradycardia refractory to atropine. Cardiopulmonary resuscitation was begun and the patient was taken to the operating room for emergency coronary artery bypass surgery. Saphenous vein bypass grafts were placed to the left anterior descending coronary artery and the left obtuse marginal branch of the left circumflex coronary artery. Despite the use of amrinone, l-norepinephrine (Levophed), dopamine and epinephrine, atrioventricular pacing, intraaortic balloon counterpulsation and a left ventricular assist device, the patient could not be weaned from cardiopulmonary bypass and he died.

Necropsy. Examination of the left ventricle disclosed subendocardial reperfusion hemorrhage, distributed circumferentially from apex to base. Serial gross examination of the excised extramural coronary arteries revealed severe diffuse coronary disease, involving nearly every segment of the left main, left anterior descending, left circumflex and right coronary arteries. Histologic examination of the coronary arteries confirmed the gross findings of severe coronary atherosclerosis distributed diffusely along the entire left anterior descending artery, with lumen cross-sectional area narrowing varying from 80.7% to 96.7% (Fig. 2, top right; Fig. 3). There were no signs of extensive disruption or dissection of the plaque or underlying wall.

Quantitative angiography. Post-hoc quantitative angiographic analysis (Fig. 2, top left) of the left anterior descending artery (before angioplasty) disclosed that the apparently nonstenotic reference segment measured 3.77 mm in diameter and 11.15 mm^2 in cross-sectional area. Quantitative analysis of the site of maximal stenosis, evaluated in the left anterior oblique projection (Fig. 1b), disclosed a lumen diameter of 0.75 mm, lumen cross-sectional area of 0.44 mm^2 and 93% stenosis. With use of the least foreshortened projection, in this case the lateral view (Fig. 1a; Fig. 2, top left), the site of most severe stenosis before coronary angioplasty measured 1.52 mm in diameter and 1.82 mm^2 in lumen cross-sectional area; percent stenosis for this site before angioplasty was 84%.

Patient 2

A 70-year old man with a 3-year history of stable angina pectoris developed a crescendo angina pattern during the 2 months before hospital admission. On the day of admission

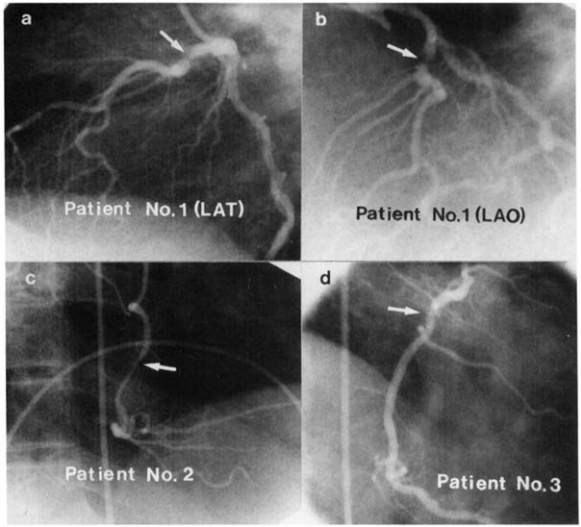


Figure 1. Representative frames from the cineangiograms. **a**, Patient 1. Selective left coronary artery injection in lateral (LAT) view. **b**, Same patient. Cranially angulated left anterior oblique (LAO) projection. **Arrows** indicate the site of focal narrowing. **c**, Patient 2. Selective angiographic study of the right coronary artery in a right anterior oblique projection demonstrated a tubular stenosis. **d**, Patient 3. Selective right coronary artery injection in a right anterior oblique projection before acute occlusion.

he presented with severe substernal chest pain that was relieved with 3 tablets of sublingual nitroglycerin.

Coronary angiography. He was initially treated with intravenous nitroglycerin and heparin. Coronary angiography was performed and demonstrated a tubular stenosis in the mid-right coronary artery (Fig. 1c), focal narrowing of the left circumflex artery and apparently nonobstructive narrowing in the left anterior descending artery. After completion of the diagnostic study, as the balloon catheter was being prepared for angioplasty, he developed severe chest pain. Repeat angiography of the right coronary artery showed no obvious change. The ST segment elevation then developed in leads II, III and aVF and failed to respond to intracoronary nitroglycerin and sublingual nifedipine. A repeat angiogram of the right coronary artery now showed complete occlusion at the level of the previous stenosis.

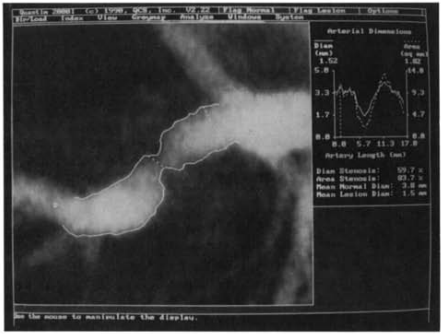
Coronary angioplasty. Emergency angioplasty, performed with a 2-mm balloon, at first appeared to successfully open the right coronary artery. However, shortly thereafter, the patient's blood pressure decreased, and repeat angiography disclosed that the artery was now occluded by apparent thrombus at the angioplasty site. Intracoronary streptokinase was then administered, and repeat balloon dilation performed. Despite these maneuvers, the patient remained hypotensive and ventricular fibrillation developed. Attempts to resuscitate the patient were unsuccessful and he died.

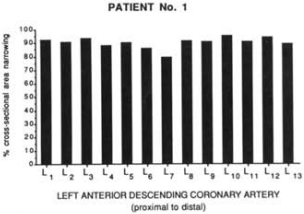
Necropsy. Examination of the heart revealed extensive subendocardial scarring of the posterior left ventricular free wall. No other evidence of an acute or remote myocardial infarction was found. Histologic examination of the coronary arteries disclosed severe diffuse three-vessel coronary artery narrowing that contrasted with the angiographic findings suggesting focal obstruction. Histologic examination of the right coronary artery in particular revealed lumen cross-sectional area narrowing that varied from 86.5% to 97.7% (Fig. 2, middle right; Fig. 4).

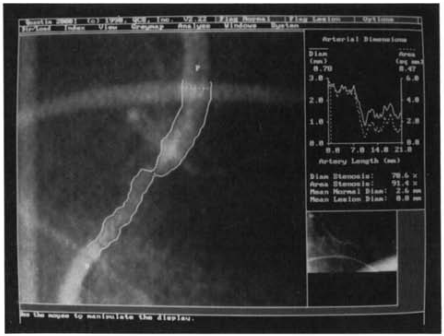
Quantitative angiography. Post-hoc quantitative angiographic analysis of the right coronary artery before angioplasty disclosed that the apparently nonstenotic reference segment measured 2.6 mm in diameter and 5.3 mm^2 in cross-sectional area. The site of most severe stenosis before coronary angioplasty measured 0.78 mm in diameter and 0.47 mm^2 in cross-sectional area; calculated percent stenosis for the site of most severe stenosis before angioplasty was 91% (Fig. 2, middle left).

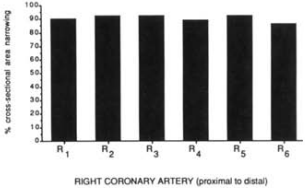
Patient 3

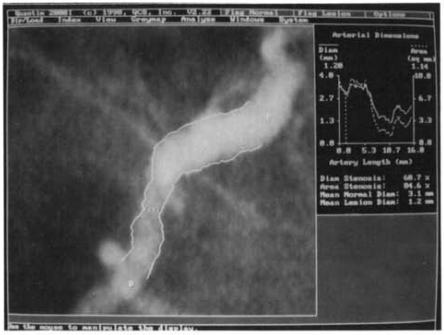
A 37-year old man presented to another hospital after the sudden onset of substernal chest pain that had begun 6 days earlier while he was driving a truck. An electrocardiogram recorded on admission to the emergency room revealed only




PATIENT No. 1
% cross-sectional area narrowing
100
90
80
70
60
50
40
30
20
10
0
L1 L2 L3 L4 L5 L6 L7 L8 L9 L10 L11 L12 L13
LEFT ANTERIOR DESCENDING CORONARY ARTERY
(proximal to distal)




PATIENT No. 2
% cross-sectional area narrowing
100
90
80
70
60
50
40
30
20
10
0
R1 R2 R3 R4 R5 R6
RIGHT CORONARY ARTERY (proximal to distal)



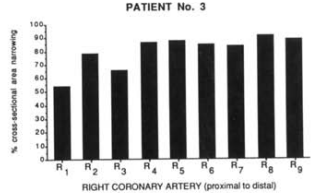
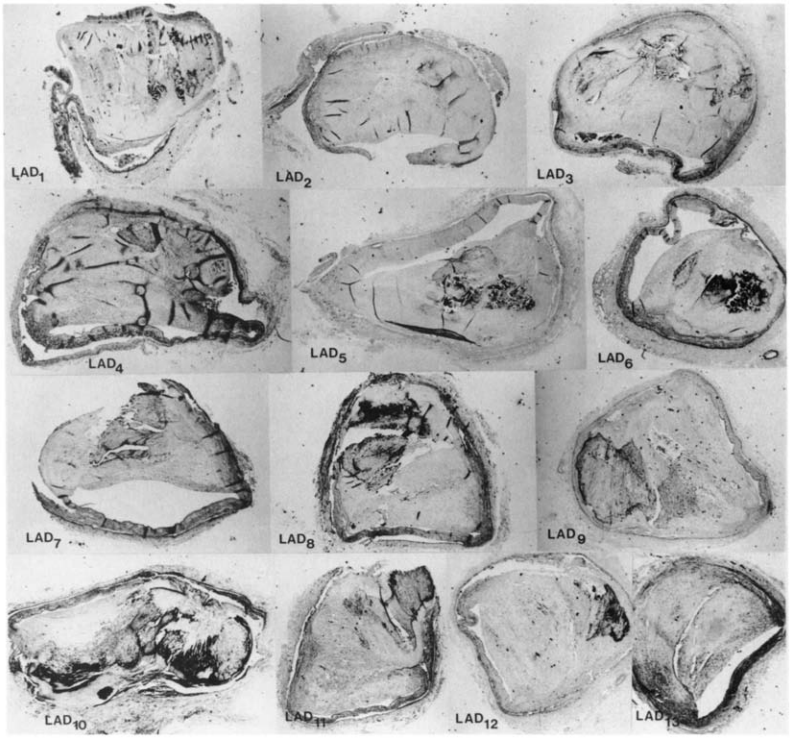

PATIENT No. 3
% cross-sectional area narrowing
100
90
80
70
60
50
40
30
20
10
0
R1 R2 R3 R4 R5 R6 R7 R8 R9
RIGHT CORONARY ARTERY (proximal to distal)

Figure 2 (opposite page). Results of quantitative angiographic analysis. Quantitatively analyzed angiograms (left) versus histograms showing percent cross-sectional area narrowing of serial 5-mm histologic sections of the same arteries (right). **Top left.** Patient 1. Quantitative analysis of focal stenosis in the proximal left anterior descending coronary artery. **Top right.** Same patient. Histogram of the percent cross-sectional area narrowing of the left anterior descending coronary artery, proximal to distal. **Middle left.** Patient 2. Quantitative analysis of the right coronary artery. **Middle right.** Patient 2. Histogram of percent cross-sectional narrowing of the right coronary artery, proximal to distal. **Bottom left.** Patient 3. Quantitative analysis of the right coronary artery. **Bottom right.** Patient 3. Histogram of percent cross-sectional area narrowing of the right coronary artery from proximal to distal. For each cine frame proximal (P) dashed lines denote reference "normal" vessel; more distal (D) dashed lines denote site of maximal narrowing. The measured diameter, area and percent stenosis are graphically and numerically depicted immediately adjacent to quantitative angiograms.

peaked T waves anteriorly. The patient's chest pain resolved after treatment with sublingual nitroglycerin and intravenous morphine. He was admitted to the coronary care unit and developed a non-Q wave myocardial infarction associated with a peak creatine kinase value of 268 (positive MB fraction). His postinfarction recovery was unremarkable and he was placed on therapy with atenolol, isosorbide dinitrate, and diltiazem. He was then transferred on hospital day 6 for coronary angiography.

Coronary angiography and angioplasty. The results of coronary angiography performed 1 day later are illustrated

Figure 3. Patient 1. Serial 5-mm histologic sections of the left anterior descending (LAD) coronary artery. The sections are arranged in sequence from proximal (LAD_1) to distal (LAD_{13}).



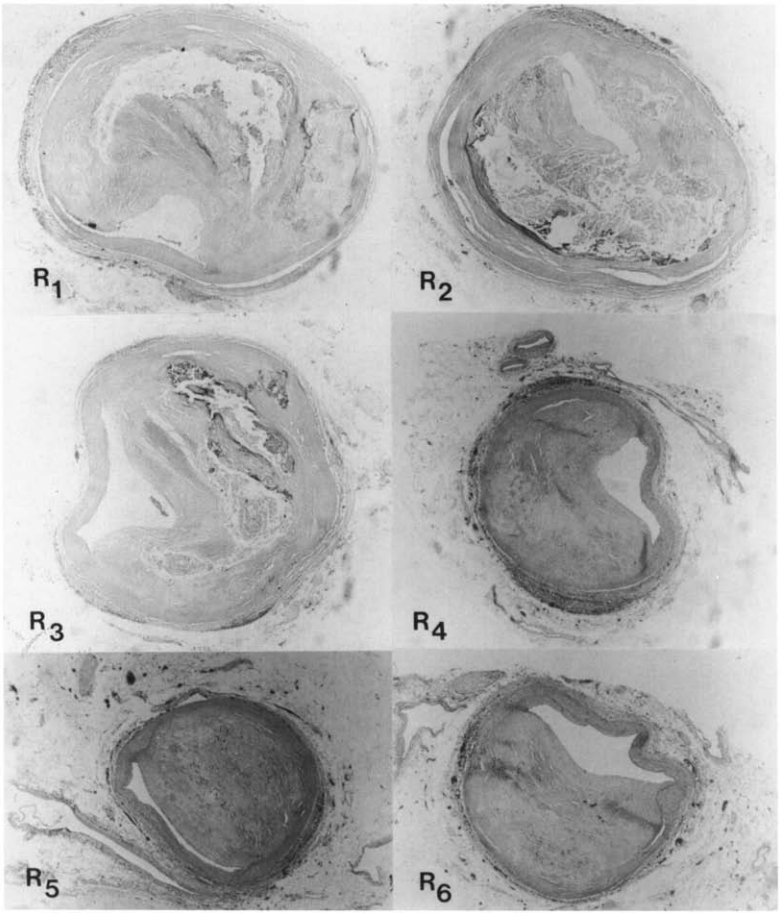


Figure 4. Patient 2. Serial 5-mm histologic sections of the right coronary artery. The sections are arranged in sequence from proximal (R_1) to distal (R_6) orientation.

for the right coronary artery in Figure 1d; no focal lesions were recognized in the left coronary circulation. Several hours after catheterization, the patient developed substernal chest pain and ST segment elevation in leads II, III and aVF. Emergency repeat angiography was performed and disclosed a total occlusion of the proximal right coronary artery. Administration of intracoronary nitroglycerin and recombinant tissue-type plasminogen activator successfully reopened the artery. Several minutes later, however, the patient reported recurrent chest pain, and repeat angiography showed that the right coronary artery was again occluded. The artery was then again successfully reopened with use of a 0.014-in. (0.036-cm) guide wire and a 3-mm balloon angioplasty catheter.

After angioplasty, however, the patient had a cardiac arrest with complete heart block; cardiopulmonary resuscitation was successfully applied and a temporary transvenous pacemaker was inserted. Repeat coronary angiography revealed that the right coronary artery was patent. Sixteen hours later, however (18 h after initial coronary angioplasty), the patient developed ventricular tachycardia, became asystolic after cardioversion and could not be resuscitated.

Necropsy. Examination revealed an acute transmural myocardial infarction involving the posterior left ventricular free wall, posterior ventricular septum and posterior right ventricular free wall. Gross examination of the external coronary arteries showed diffuse severe atherosclerosis involving all three major coronary arteries. Histologic examination of the right coronary artery in particular revealed lumen cross-sectional area narrowing that varied from 55.6% to 92.7% (Fig. 2, bottom right; Fig. 5).

Quantitative coronary angiography. Post hoc quantitative angiographic analysis of the right coronary artery (before angioplasty) disclosed that the angiographically apparently nonstenotic reference segment measured 2.48 mm in diameter and 4.53 mm^2 in cross-sectional area. Retrospective examination of the initial diagnostic angiogram disclosed a focal-appearing stenosis at the site of subsequent total occlusion where the most severe stenosis measured 1.2 mm in diameter and 1.14 mm^2 in cross-sectional area; calculated percent stenosis for the site of most severe stenosis before angioplasty was 85% (Fig. 2, bottom left).

Discussion

Liabilities of coronary angiography. In the 3 decades that have passed since coronary arteriography was introduced into clinical practice (20), certain liabilities associated with this technique have been identified, studied and, in some cases, solved. In patients with coronary heart disease studied at necropsy, for example, it was observed that the residual nonoccluded lumen was often eccentric in location and slitlike in shape (21); because such a lumen may allow contrast opacification of most or all of the lumen diameter in a given plane, the severity of lumen narrowing could be underestimated. Attempts to solve this issue led to the routine recording of multiple, including, orthogonal views (22).

It was subsequently recognized, however, that variations in coronary anatomy, body habitus and lesion location often precluded accurate angiographic depiction of a putative lesion in its narrowest dimensions because of overlap with other vessels and foreshortening of the vessel of interest. This issue was answered in large measure by the development of more versatile angiographic gantries allowing a greater range of nonaxisymmetric views.

Even when a lesion could be successfully isolated and depicted in its most severely narrowed orientation, visual estimates of the resulting degree of lumen narrowing varied significantly among different observers (23–26), leading to both occasional inaccuracies and limited reproducibility. Quantitative coronary arteriography, proposed initially by Brown et al. (27), validated by Gould et al. (28) and subsequently modified to include computer-assisted automated edge detection (29–32), resulted in more objective angiographic analyses and thereby aided the precision of lesion assessment.

Previously reported necropsy findings. Histopathologic studies of human coronary arteries, however, disclosed yet an additional feature potentially limiting the accuracy of angiographic analyses, namely, the fact that coronary atherosclerosis is characteristically diffuse (14–17). Diffuse narrowing forces the angiographer to compare sites of maximal narrowing to adjacent sites that may be less, but still severely, narrowed, seldom leaving the angiographer with a truly normal lumen diameter from which estimates of relative lumen narrowing can be accurately derived.

The impact of this anatomic fact on the angiographic analysis of lumen narrowing has been documented by previous investigators in several ways. Diffuse narrowing has been indicted, for example, as the principal basis for pathologically documented angiographic underestimation of coronary narrowing. In one such study (7), among 465 5-mm segments of coronary artery examined histologically from 10 patients, 209 (45%) were narrowed by 76% to 100% and 139 (29%) were narrowed by 51% to 75%; only 45 (<10%) of the total 465 sections were narrowed by <26% in cross-sectional area.

Glagov et al. (33) and others (34) have demonstrated that even when the degree of narrowing resulting from diffusely distributed plaque is less severe, the accuracy of coronary angiography may be compromised. This is because mild to moderate atherosclerosis is associated with compensatory arterial dilation; consequently, in arteries narrowed by up to 40% in cross-sectional area, absolute lumen dimensions may remain relatively well preserved.

White et al. (12) used intraoperative assessment of reactive coronary hyperemia to determine the physiologic importance of coronary stenoses identified by quantitative angiography. In 39 lesions with apparently discrete coronary narrowing, measurement of percent stenosis by coronary angiography was not significantly correlated ($r = -0.25$)

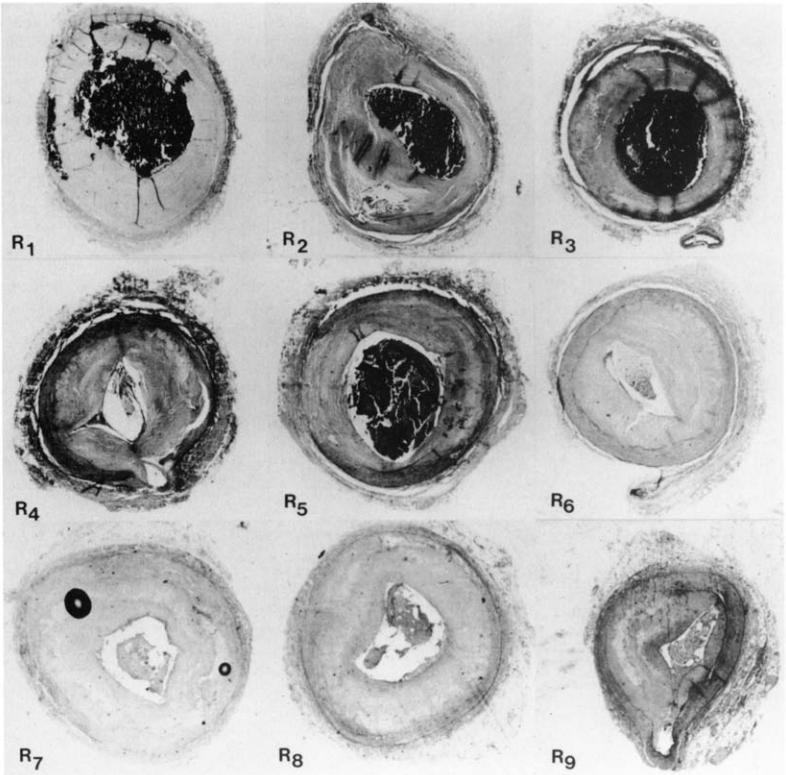


Figure 5. Patient 3. Serial 5-mm histologic sections of the right coronary artery. The sections are arranged in sequence from proximal (R_1) to distal (R_9).

with the reactive hyperemic response. These investigators (12) concluded that the most important factor responsible for this documented discrepancy was "the usually diffuse nature of coronary atherosclerosis."

Even when the coronary segment of interest is relatively short, elimination of a truly normal baseline by submaximal narrowing constitutes a serious liability. The left main coronary artery, for example, is the shortest of the major extramural coronary arteries; however, when it is narrowed to an equivalent degree over its entire length, identification of left main coronary artery disease may be missed (9,35). Beatt et al. (36) demonstrated that the development of mild to moderate narrowing in the segments directly adjacent to sites of stenosis treated by coronary angioplasty may lead one to underestimate the degree of restenosis apparent upon repeat angiography.

Identification of diffuse narrowing. The angiographic and necropsy findings in the present three patients document that previous concerns regarding coronary narrowing that remains occult by virtue of diffuse distribution extend to the evaluation of patients being considered for coronary angio-

plasty. The angiographic finding of focal narrowing has long been regarded as the essential criterion for coronary angioplasty (37,38). Because of the limited number of patients studied at necropsy shortly after angioplasty, the prevalence of diffuse disease masquerading as a nearly normal baseline remains undetermined. However, the present three cases suggest that such anatomy may be more common than has been previously recognized.

Algorithms developed for quantitative angiography diminish to some extent the liabilities posed by diffusely diseased vessels. Harrison et al. (11), for example, found that measurement of minimal lumen diameter improved the correlation between lesion assessment by coronary angiography and reactive hyperemic response (r = 0.73). Beatt et al. (36) showed that use of the interpolated reference diameter permitted more accurate assessment of restenosis after angioplasty. As our three cases illustrate, however, unless the absolute lumen dimensions can be interpreted to distinguish nonobstructed, diminutive arteries from arteries that are diffusely and severely narrowed, the extent of coronary disease in patients undergoing coronary angioplasty may nevertheless be underestimated.

In the present three cases, the extent to which diagnostic angiography failed to reflect severe, diffuse coronary artery disease may have contributed to each patient's death. Not only was coronary narrowing more diffuse and more severe than anticipated in the artery selected for angioplasty, but also, the other extramural arteries were similarly affected. As a result, the ischemic burden at the time of balloon inflation was underestimated in these three patients. Had each been recognized to have diffuse three-vessel coronary artery narrowing, it is questionable—at least in the elective cases of Patients 1 and 2—that angioplasty would have been recommended.

How may the assessment of patients such as those described in this report be improved? Previous investigations (39), including those of Harrison et al. (11) and White et al. (12) cited earlier, have indicated that complementary use of physiologic tests, such as assessment of coronary flow reserve, may serve to distinguish diffusely diseased arteries from nonobstructed vessels of lesser caliber. In certain patients being considered for coronary angioplasty, however, such as Patients 1 and 2 in the present report, the issue is not whether the lesions recognized by angiography are capable of causing myocardial ischemia, but rather to what extent the vessels are in fact compromised. Gould (39) previously suggested that the ideal instrument for assessment of stenosis severity should allow composite analysis of both relative and absolute percent narrowing, as well as lesion length, absolute diameter of the normal artery and blood viscosity. Certain new imaging techniques, such as intravascular ultrasound (40–43), which permit most of these measurements, may ultimately provide more accurate definition of the diffusely diseased artery.

Potential limitations. Because pathologic examination was employed as the reference standard in this report, certain limitations of this methodology must be acknowledged. First, the coronary arteries from Patients 1 and 2 were examined at necropsy without pressure distension. Wolinsky and Glagov (44) previously demonstrated a corresponding increase in the radius of rabbit aortas examined at necropsy as intraluminal distending pressure is increased from 5 to 80 mm Hg. Second, Siegel et al. (45) previously demonstrated that in nondistended vessels with moderate to severe atherosclerosis, histologic processing leads to a reduction in total arterial area without a corresponding reduction in the area of the residual arterial lumen. Thus the former may lead to overestimation of lumen narrowing, whereas the latter may lead to its underestimation. It is difficult to determine with certainty the extent to which each of these factors affected pathologic analyses in the present three cases. However, because the issue in the present report concerned the distribution rather than the absolute dimensions of coronary artery narrowing, the validity of the observations reported here appears to be preserved.

References

1. Gray CR, Hoffman HA, Hammond WS, Miller KM, Ottesehn RO. Correlation of arteriographic and pathologic findings in coronary arteries in man. Circulation 1962;26:494–9.
2. Esterman JH, Achor RWP, Kincaid OW, Brown AL. Atherosclerotic disease of the coronary arteries: a pathologic-radiologic correlative study. Circulation 1962;26:1288–95.
3. Kemp HG, Evans H, Elliott WC, Gorlin R. Diagnostic accuracy of selective coronary cinearteriography. Circulation 1967;36:526–33.
4. Vlodaver Z, Frech R, Van Tassel RA, Edwards JE. Correlation of the antemortem coronary arteriogram and the postmortem specimen. Circulation 1973;47:162–9.
5. Grondin CM, Dyrda I, Pasternac A, Campeau L, Bourassa MG, Lesperance J. Discrepancies between cineangiographic and postmortem findings in patients with coronary artery disease and recent myocardial revascularization. Circulation 1974;49:703–8.
6. Hutchins GM, Bulkley BH, Radolfi RL, Griffith LSC, Lohr FT, Piasio MA. Correlation of coronary arteriograms and left ventriculograms with postmortem studies. Circulation 1977;56:32–7.
7. Arnett EN, Isner JM, Redwood DR, et al. Coronary artery narrowing in coronary heart disease: comparison of cineangiographic and necropsy findings. Ann Intern Med 1979;91:350–6.
8. Waller BF, Roberts WC. Amount of narrowing by atherosclerotic plaque in 44 nonbypassed and 52 bypassed major epicardial coronary arteries in 32 necropsy patients who died within 1 month of aortocoronary bypass grafting. Am J Cardiol 1980;46:956–62.
9. Isner JM, Kishel JJ, Kent KM, Ronan RA, Ross AM, Roberts WC. Accuracy of angiographic determination of left main coronary arterial narrowing: angiographic-histologic correlative analysis in 28 patients. Circulation 1981;63:1056–64.
10. Gould KL, Lipscomb K, Hamilton GW. Physiologic basis for assessing critical coronary stenosis. Am J Cardiol 1974;33:87–94.
11. Harrison DG, White CW, Hiratzka LF, et al. The value of lesion cross-sectional area determined by quantitative coronary angiography in assessing the physiologic significance of proximal left anterior descending coronary arterial stenoses. Circulation 1984;69:1111–9.
12. White CW, Wright CB, Doty DD, et al. Does visual interpretation of the coronary arteriogram predict the physiologic importance of coronary stenosis? N Engl J Med 1984;310:819–24.
13. Kirkeeide RL, Gould KL, Parsel L. Assessment of coronary stenoses by myocardial perfusion imaging during pharmacologic coronary vasodilation. VII. Validation of coronary flow reserve as a single integrated functional measure of stenosis severity reflecting all its geometric dimensions. J Am Coll Cardiol 1986;7:103–3.

14. Roberts WC, Jones AA. Quantitation of coronary arterial narrowing at necropsy in sudden coronary death: analysis of 31 patients and comparison with 25 control subjects. Am J Cardiol 1979;44:239–45.
15. Roberts WC, Virmani R. Quantification of coronary arterial narrowing in clinically-isolated unstable angina pectoris: an analysis of 22 necropsy patients. Am J Med 1979;67:792–9.
16. Virmani R, Roberts WC. Quantification of coronary arterial narrowing and of left ventricular myocardial scarring in healed myocardial infarction with chronic, eventually fatal, congestive cardiac failure. Am J Med 1980;68:831–8.
17. Roberts WC, Jones AA. Quantification of coronary arterial narrowing at necropsy in acute transmural myocardial infarction: analysis and comparison of findings in 27 patients and 22 controls. Circulation 1980;61:705–10.
18. Marcus ML, Harrison DG, White CW, McPherson DD, Wilson RF, Kerber RE. Assessing the physiologic significance of coronary obstruction in patients: importance of diffuse undetected atherosclerosis. Prog Cardiovasc Dis 1988;31:39–56.
19. Isner JM, Donaldson RF, Fortin AH, Tischler A, Clarke RH. Attenuation of the media of coronary arteries in advanced atherosclerosis. Am J Cardiol 1986;58:937–9.
20. Sones FM, Jr. Acquired heart disease: Symposium on the present and future of cineangiocardiography. Am J Cardiol 1959;3:700–4.
21. Vladaver Z, Edwards JE. Pathology of coronary atherosclerosis. Prog Cardiovasc Dis 1971;14:256–74.
22. Spears JR, Sanborn T, Baim DS, Paulin S. The minimum error in estimating coronary luminal cross-sectional area from cineangiographic diameter measurements. Cathet Cardiovasc Diagn 1983;9:119–128.
23. Bjork L, Spindola-Franco H, Van Houten FX, Cohn PFF, Adams DF. Comparison of observer performance with 16 mm cinefluorography and 70 mm camera fluorography in coronary arteriography. Am J Cardiol 1975;36:474–8.
24. Zir LM, Miller SW, Dinsmore RE, Gilbert JP, Harthorne JW. Interobserver variability in coronary angiography. Circulation 1976;53:627–32.
25. DeRouen TA, Murray JA, Owen W. Variability in the analysis of coronary arteriograms. Circulation 1977;55:324–8.
26. Meyers MG, Shulman HS, Saibil EA, Naqvi SZ. Variation in measurement of coronary lesions on 35 mm and 70 mm angiograms. Am J Roentgenol 1978;130:913–5.
27. Brown BG, Bolson E, Frimer M, Dodge HT. Quantitative coronary arteriography: estimation of dimensions, hemodynamic resistance, and atheroma mass of coronary artery lesions using the arteriogram and digital computation. Circulation 1977;55:329–37.
28. Gould KL, Kelley KO, Bolson EL. Experimental validation of quantitative coronary arteriography for determining pressure-flow characteristics of coronary stenosis. Circulation 1982;66:930–7.
29. Alderman EL, Berte LE, Harrison DC, et al. Quantitation of coronary artery dimensions using digital image processing. Soc Photo-Optical Instrum Engineers-Digital Radiography 1981;314:273–8.
30. Sanders WJ, Alderman EL, Harrison DC. Coronary artery quantitation using digital image processing techniques. IEEE Comput Cardiol 1979;7:15–20.
31. Reiber JHC, Boorsma F, Tan HS, et al. Computer processing of coronary occlusions from x-ray arteriograms. INSERM 1979;88:79–92.
32. Serruys PW, Reiber JHC, Wijns W, et al. Assessment of percutaneous transluminal coronary angioplasty by quantitative coronary angiography: diameter versus densitometric area measurements. Am J Cardiol 1984;54:482–8.
33. Glagov S, Weisenberg E, Zarins CK, Stankunavicius R, Kolettis GK. Compensatory enlargement of human atherosclerotic coronary arteries. N Engl J Med 1987;316:1371–5.
34. McPherson DD, Sims SJ, Hiratzka LF, et al. Coronary arterial remodeling studies by high-frequency epicardial echocardiography: an early compensatory mechanism in patients with obstructive coronary atherosclerosis. J Am Coll Cardiol 1991;17:79–86.
35. Lipton MJ, Pfeifer JF, Murphy ML, Hultgren HN. Dangers of left main coronary artery lesions: angiographic technique and evaluation. Invest Radiol 1977;12:4–7–51.
36. Beatt KJ, Luijten HE, DeFeyter PJ, et al. Change in diameter of coronary artery segments adjacent to stenosis after percutaneous transluminal coronary angioplasty: failure of percent diameter stenosis measurement to reflect morphologic changes induced by balloon dilation. J Am Coll Cardiol 1988;12:315–23.
37. Grüntzig AR, Senning A, Siegenthaler WE. Nonoperative dilatation of coronary-artery stenosis: percutaneous transluminal coronary angioplasty. N Engl J Med 1979;301:61–8.
38. Ryan TJ, Faxon DP, Gunnar RM, et al. Guidelines for percutaneous transluminal coronary angioplasty. J Am Coll Cardiol 1988;12:529–45.
39. Gould KL. Quantification of coronary artery stenosis in vivo. Circ Res 1985;57:341–53.
40. Nissen SE, Grines CL, Gurley JC, et al. Application of a new phased-array ultrasound imaging catheter in the assessment of vascular dimensions: in vivo comparison to cineangiography. Circulation 1990;81:660–6.
41. Davidson CJ, Sheikh KH, Harrison JK, et al. Intravascular ultrasonography versus digital subtraction angiography: a human in vivo comparison of vessel size and morphology. J Am Coll Cardiol 1990;16:633–6.
42. Isner JM, Rosenfield K, Kelly S, et al. Percutaneous intravascular ultrasound examination as an adjunct to catheter-based interventions: preliminary experience in patients with peripheral vascular disease. Radiology 1990;175:51–70.
43. Fobin JM, Mallery J, Mahon D, et al. Intravascular ultrasound imaging of human coronary arteries in vivo: analysis of tissue characterizations with comparison to in vitro histological specimens. Circulation 1991;83:913–26.
44. Wolinsky H, Glagov S. Structural basis for the static mechanical properties of aortic media. Circ Res 1964;14:400–13.
45. Siegel RJ, Swan R, Edwalds G, Fishbein MC. Limitations of postmortem assessment of human coronary artery size and luminal narrowing: differential effects of tissue fixation and processing on vessels with different degrees of atherosclerosis. J Am Coll Cardiol 1985;5:342–6.