Title

Videodensitometric determination of minimum coronary artery luminal diameter before and after angioplasty

Journal
The American Journal of Cardiology, 59(1)

ISSN
0002-9149

Authors
Tobis, Jonathan
Nalcioglu, Orhan
Johnston, Warren D
et al.

Publication Date
1987

DOI
10.1016/s0002-9149(87)80065-6

Videodensitometric Determination of Minimum Coronary Artery Luminal Diameter Before and After Angioplasty

JONATHAN TOBIS, MD, ORHAN NALCIOGLU, PhD, WARREN D. JOHNSTON, MD,
LIAN QU, MS, TIM REESE, BS, DAVID SATO, MD, WERNER ROECK, Eng Grad,
STEVE MONTELLI, CRT, and WALTER L. HENRY, MD

Quantitative measurements of coronary stenoses were made from digital coronary angiograms in 19 patients before and after percutaneous transluminal coronary angioplasty (PTCA). Two methods of measurement were compared. Mean stenosis before PTCA was 67 ± 10% by the edge detection method and 67 ± 12% by videodensitometry (difference not significant). After PTCA, the mean stenosis was 32 ± 14% by edge detection and 30 ± 13% by videodensitometry (difference not significant). In addition, a new method was developed to rapidly calculate the absolute minimum luminal area and diameter by videodensitometry. The minimum luminal diameter before PTCA was 1.0 ± 0.5 mm and after PTCA increased to 2.4 ± 0.5 mm ($p < 0.001$). The validity of the videodensitometric method was analyzed in a series of Lucite phantom studies, which suggested that when there is an irregular angiographic appearance, the densitometric method may be more accurate than standard edge detection methods. Digital acquisition of coronary angiograms provides a means for rapid application of quantitative analysis during coronary interventional procedures.

(Am J Cardiol 1987;59:38–44)

The results of percutaneous transluminal coronary angioplasty (PTCA) are judged primarily by the amount of improvement in percent stenosis of the dilated coronary segment.[1,2] Although the edge detection method is the standard for measuring percent stenosis, the stenotic segment may not be circular in cross section and may be misrepresented by edge detection methods.[3-8] Another problem in assessing the success of angioplasty by this method is that the procedure may produce tearing and controlled dissection of plaque.[9,10] Consequently, the lumen may not be smooth or symmetric after angioplasty.

Videodensitometry is a method of estimating percent stenosis that has the potential advantage of being independent of geometric assumptions about the shape of the coronary lumen.[11-14] The first purpose of this study was to compare percent diameter stenosis measured by the edge detection technique with those measured by the videodensitometric method before and after PTCA. The second purpose was to develop a method of calculating absolute minimum luminal area by videodensitometry. Because percent stenosis is a relative value that is dependent on the presence of a normal segment, changes in absolute minimum luminal area or diameter may be more meaningful than changes in percent stenosis.

Methods

Digital angiograms were recorded in the clinical cardiac catheterization laboratory using a Siemens Cardioskop-U unit and a Gigantos Optimatic x-ray generator. Images were exposed onto a 7-inch image intensifier at a nominal focal spot of 1.2 mm. The images were converted in real time at either 8 or 30 frames/s by an on-line video image processor (Fischer DA-100) into a 512 × 512 × 8 bit matrix and stored

---

From the Division of Cardiology and Department of Radiology, University of California, Irvine, Orange, California. This study was supported in part by grant RO1 HL31440-01A1 from the National Institutes of Health, Bethesda, Maryland. Manuscript received April 23, 1986; revised manuscript received August 4, 1986, accepted August 6, 1986.

Address for reprints: Jonathan Tobis, MD, Division of Cardiology, Rt. 81, University of California, Irvine Medical Center, 101 City Drive South, Orange, California 92668.

digitally on a 475-megabyte rapid parallel transfer disk. Computer programs within the system permitted rapid access to image enhancement algorithms such as 4-fold digital magnification, mask mode subtraction and software graphics for observer identification of artery boundaries or measurement of distances on an x-y coordinate scale as described previously.[15] In addition, software programs were developed to perform videodensitometric calculations. The digital images were logarithmically amplified to correct for exponential x-ray absorption so that the digital number in the 8-bit deep memory (equivalent to a digital gray scale of 256 shades) corresponded to the thickness of the material that the x-rays traversed.[16] Phantom studies were performed to test the capability of the digital angiographic system to determine percent stenosis and minimum luminal diameter.

Phantom study I: The first series of phantoms were aluminum cylinders that were machine lathed to diameters of 1.0, 1.5, 2.0, 3.0 and 4.0 mm. Aluminum was chosen because its attenuation coefficient approximates the iodine x-ray absorption of a 20% concentration of meglumine diatrizoate (Renografin 76). Digital angiograms were taken of the aluminum pin phantoms and a calculation of relative stenosis was derived by comparing each of the smaller diameter pins with the 4.0-mm-diameter pin. The absolute diameter of the pins was known so that measurements of relative stenosis by different techniques could be compared with the actual measurements. Percent stenosis was calculated from unsubtracted images by the edge detection method. The digital images were then processed by mask mode subtraction to diminish background densities. Percent stenosis between the pin phantoms was recalculated from the subtracted images by edge detection as well as videodensitometry.

Phantom study II: In this portion of the study, a new method was evaluated that had been developed to perform densitometric measurements from unsubtracted digital images. This method, called the "background interpolation method," calculated the gray scale density at the 4 corners of a region of interest (ROI) as outlined by an observer. A smooth curve was generated to estimate the topographic background variation within the ROI (Fig. 1). Two algorithms were tested for fitting the interpolated topographic background. The first formula assumed a simple linear variation of background densities between the 4 corners of the ROI. The background profile curve was created by weighting the background density of each pixel in the ROI by its linear proximity to each of the corners. The second algorithm applied a least-mean-squares fit to a polynomial equation of the density curve at the corner pixels to estimate the background component curve within the entire ROI. Each of the 2 interpolated background density profiles were then subtracted from the densities within the ROI. The resulting density value corresponded to the relative volume of the pin. A comparison of the densities between phantom pins yielded a measure of relative volumes, which represents percent area stenosis when it is divided by the height of the ROI. Percent diameter stenosis was then derived by assuming a circular cross section.

The aluminum pin phantoms were placed inside a chest phantom that consisted of human ribs and Lucite comparable to the x-ray density of a human thorax. Because clinical studies revealed that a significant amount of misregistration artifact occurred in mask mode–subtracted digital images due to patient motion, the second phantom study was performed to determine the effect of motion and the resulting misregistration artifact on densitometric calculations. Digital images were obtained of the thorax phantom alone to be used as a mask during subtraction and of the thorax plus the pin phantoms. The thorax was then displaced 1 cm laterally to create misregistration or motion artifact relative to the original thorax mask image. Densitometric calculations of percent stenosis were performed on the mask mode–subtraction images with and without motion, and were compared with the densitometric measurements by the background interpolation method performed on the unsubtracted images.

Phantom study III: Because the edges of tight stenoses may be difficult to measure by boundary recognition techniques, the third phantom study was performed to assess the ability to determine absolute luminal diameters from digital images using a comcombination of edge detection and videodensitometric methods. A series of phantoms were made from Lucite

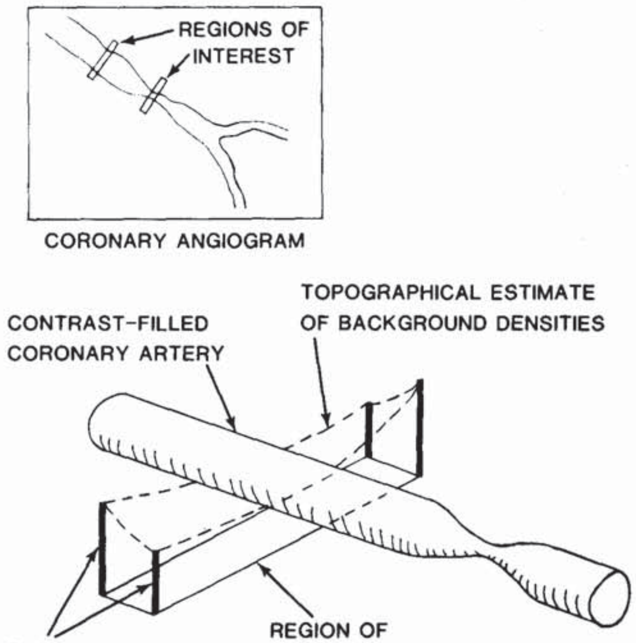

FIGURE 1. Method of performing the interpolated background subtraction. The operator places a small region of interest at the stenotic and nonstenotic segments. The computer program then estimates background contribution at each pixel within the region of interest based on its relative distance from the pixels at the 4 corners of the region of interest.

blocks with precision drilled holes at 0.5, 1.0, 1.5, 2.0, 3.0 and 4.0 mm. The tubular holes were filled with undiluted iodine contrast. An 8Fr coronary angiographic catheter with an external diameter of 2.55 mm was used to calibrate the pixel size of the digital images. The edges of each of the phantoms were defined by the observer and the width in pixels was used to calculate the absolute diameter by the edge detection method. In addition, an algorithm was developed that combined edge detection with videodensitometry to calculate minimum luminal diameter. In this method, the edges of the catheter and the 4.0 mm "normal" lumen were defined by the observer to calibrate the pixel width and account for x-ray magnification. A ROI rectangle was positioned over the 4.0-mm "normal" phantom lumen and over each of the smaller "stenotic" phantom lumens. The density across the width of the lumens was calculated by the background interpolation method relative to the density of the 4.0 mm lumen to derive a percent cross-sectional area stenosis. The percent diameter stenosis was then calculated assuming that the lumens were circular in cross section. The absolute diameter of the smaller "stenotic" lumen was then derived from a ratio of the relative densities compared with the calibrated diameter of the 4.0-mm lumen:

$$D_s = (DEN_s)^{1/2} \times D_n \, (DEN_n)^{1/2}$$

where D_s = diameter of the stenotic segment, D_n = diameter of the normal segment, DEN_s = density of stenotic segment and DEN_n = density of the normal segment.

Phantom study IV: To assess the ability of edge detection and densitometric techniques to accurately quantitate asymmetric arterial lumens, a fourth phantom model was made. This Lucite model had 2 pairs of machine-drilled holes, each 1.0 mm in diameter. Two holes were oriented with their long axis in a plane parallel to the image intensifier face and 2 holes were placed in front of each other relative to the plane of the image intensifier. The holes were filled with contrast media and digital images were obtained (Fig. 2). Although the suerimposed lumens had the same density as the other 2 lumens combined, the apparent diameter (by edge detection) of the superimposed lumens was 50% less.

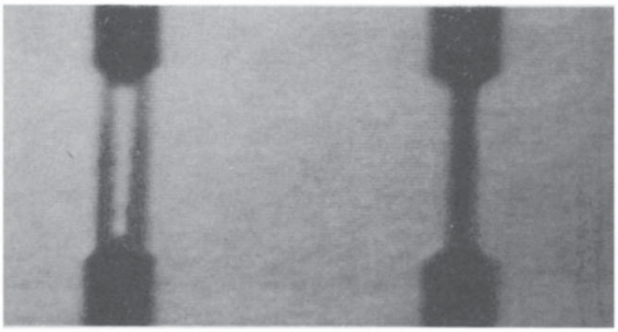

FIGURE 2. In this digital image of a Lucite phantom filled with radiopaque contrast, the large lumens are 4.0 mm in diameter and the small lumens are 1.0 mm. The small lumens (*left*) are positioned side by side, but the 2 other lumens (*right*), are placed in front of the other. This model was used to assess the ability of the densitometric method to determine stenoses that could not be readily visualized by the edge detection technique.

Clinical study: Digital coronary angiograms of 24 patients who were undergoing PTCA were recorded before and after the procedure in orthogonal right and left anterior oblique projections with caudocranial angulation. The images were obtained at 8 or 30 frames/s in a 512 × 512 × 8 bit matrix. A detailed description of our digital acquisition technique and validation studies compared with 35-mm film has been reported.[15] After the procedure, the unsubtracted coronary images both before and after PTCA were recalled from the digital disk, magnified 4 times and displayed on the computer monitor for quantitative analysis. Five patient studies were excluded because the stenosis was not well visualized in both projections either before or after PTCA. One of the 5 patient studies was excluded because the metal wires in the sternum from previous coronary bypass surgery obscured the stenosis in 1 projection and interfered with the densitometric measurement.

Nineteen remaining sets of digital coronary angiograms were analyzed by 2 independent observers using the edge detection and background interpolation videodensitometric algorithms (as already described). To have both observers measure the same normal and stenotic coronary segments, the first observer took a Polaroid picture of the placement of the ROI boxes over the 2 segments. In this manner, the second observer knew which segments were analyzed from the coronary angiogram, and yet the individual determination of edge boundaries and the specific placement of the ROI was independently performed. The measurements of percent stenosis by the edge detection and videodensitometric techniques were compared by linear regression analyses both before and after PTCA in both right anterior oblique and left anterior oblique projections.

Results

Phantom I results: Five repetitive measurements were made by each observer with the edge detection technique on the subtracted and unsubtracted images. Subtracted phantom images were also measured by the videodensitometric method. Mean values for the calculated percent stenosis are shown in Table I.

Phantom II results: Densitometric measurements of percent stenosis were performed 5 times for each of the 3 techniques: mask mode subtraction without motion artifact, mask mode subtraction with motion artifact and background interpolation on unsubtracted images. Results of the different measurements compared with the actual relative stenoses are shown in Table II. Of note, the 2 methods for estimating background by the interpolation method (i.e., the linear or polynomial curve fit) yielded similar results in the phantom models and in later clinical studies.

Phantom III results: Five repetitive measurements of the absolute luminal diameter of the contrast-filled

TABLE I Edge Detection Versus Videodensitometry Phantom Study (Aluminum Pins)

Actual % Stenosis	Videodensitometry Subtracted	Edge Detection	
		Unsubtracted	Subtracted
50% (2.0/4.0 mm)	52.3 ± 0.7	53.3 ± 0.0	55.8 ± 1.8
63% (1.5/4.0 mm)	66.8 ± 1.8	61.3 ± 3.0	69.1 ± 3.3
75% (1.0/4.0 mm)	80.3 ± 0.9	69.3 ± 6.0	88.2 ± 4.0

TABLE II Densitometric Phantom Study (Motion Present) (Lucite Block Holes Filled with Contrast)

Actual % Stenosis	Mask Mode Subtraction		Interpolated Background Subtraction
	No Motion	Motion	
50% (2.0/4.0 mm)	52.2 ± 0.7	64.7 ± 10.2	57.7 ± 4.1
63% (1.5/4.0 mm)	66.8 ± 1.8	50.4 ± 19.6	64.3 ± 4.1
75% (1.0/4.0 mm)	80.3 ± 0.9	35.0 ± 26.7	78.3 ± 6.8

TABLE III Absolute Luminal Diameter Edge Detection Versus Videodensitometry (Lucite Block Holes Filled With Contrast)

Actual Diameter (mm)	Edge Detection	Videodensitometry
0.5	0.6 ± 0.1	0.6 ± 0.1
1.0	1.0 ± 0.2	1.0 ± 0.1
1.5	1.6 ± 0.1	1.6 ± 0.1
2.0	2.1 ± 0.1	1.9 ± 0.1
3.0	3.1 ± 0.1	2.8 ± 0.0

Lucite phantoms were made by 2 independent observers by the edge detection and videodensitometric methods. Mean values are shown in Table III.

Phantom IV results: For the first pair of Lucite block holes, which were 1 mm apart and parallel to the plane of the image intensifier, the edge detection method detected 2 separate lumens; each one was 25% the diameter of the representative normal 4.0-mm lumen, to yield a 50% total diameter stenosis (Fig. 2). The second pair of holes was superimposed, and thus the edge detection method yielded a 75% stenosis relative to the 4.0-mm lumen. The ROI for the videodensitometric method was placed across both holes of the first pair in the image of the phantom and a diameter stenosis of 50% was calculated relative to the 4.0-mm-diameter lumen. The ROI was then placed over the superimposed second pair of holes and an effective diameter stenosis of 50% was also measured.

Clinical results: A comparison of the edge detection and videodensitometric techniques for measuring percent diameter stenosis before and after PTCA is shown in Figure 3. For the purpose of this comparison between techniques, the measurements from the 2 observers were averaged and measurements from both left anterior oblique and right anterior oblique projections were included. The correlation coefficient between the techniques was 0.90, with a standard error of the estimate (SEE) of 9.9%. Before PTCA the mean percent stenosis was 67 ± 10% by edge detection and 67 ± 12% by videodensitometry (difference not significant). After PTCA the mean percent stenosis was 32 ± 14% by edge detection and 30 ± 13% by videodensitometry (difference not significant). When measurements of percent stenosis made from the differentprojections were separated out, there was still no significant difference between the edge detection and videodensitometric techniques. In the right anterior oblique projection, edge detection and densitometry were closely correlated ($r = 0.88$, SEE = 11.7); in the left anterior oblique projection the 2 techniques were similarly correlated ($r = 0.88$, SEE = 11.5).

The absolute minimum luminal diameter was calculated by the combined edge and densitometric method to be 1.0 ± 0.5 mm before PTCA and 2.4 ± 0.5 mm after PTCA ($p < 0.001$). The mean measurement of the normal segment was 3.3 ± 0.6 mm before PTCA and was unchanged at 3.3 ± 0.6 mm in images taken after completion of PTCA.

The comparison between observers for the percent stenosis before and after PTCA is shown in Figure 4 for the videodensitometric method and in Figure 5 for the edge detection method. The correlation coefficient was 0.88 between observers for the densitometric method and for the edge detection technique it was 0.87.

The comparison of percent stenosis measured by edge detection in the 2 orthogonal projections is demonstrated in Figure 6. The correlation coefficient was 0.80 and the SEE was 12.8%. The data for percent stenosis measured by videodensitometry from the 2 orthogonal projections are shown in Figure 7. The correlation coefficient was 0.79 and SEE was 14.3%.

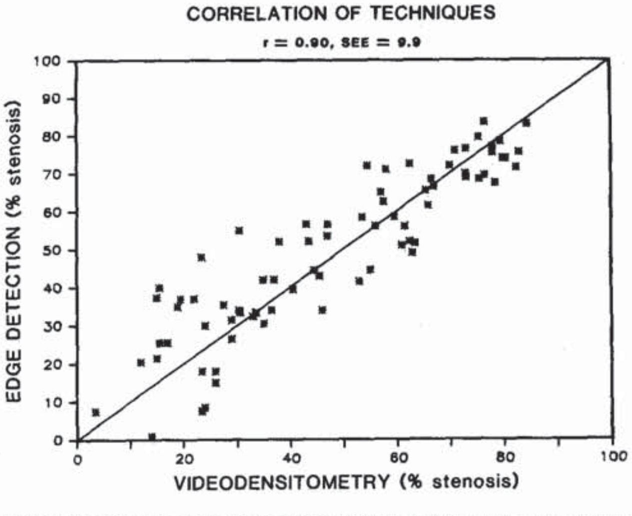

FIGURE 3. Comparison of the videodensitometric and edge detection methods for measuring percent stenosis. The measurements from both observers were averaged and data from both right anterior oblique and left anterior oblique projections were included. In this and subsequent figures, the line of identity is provided. The regression equation was $y = 0.97x + 0.2$.

Several conclusions drawn from the results of the phantom studies influenced our software development and our approach to performing quantitative coronary analysis with digital acquisition. The first phantom study indicated that videodensitometry has accuracy comparable to edge detection methods down to a luminal diameter of 1.0 mm. However, when the edge detection method was applied to subtracted images, a significant overestimation of percent stenosis occurred.

The second phantom study documented that misregistration artifact significantly interferes with the densitometric determination of percent stenosis. However, the interpolated background subtraction technique corresponded closely with the known actual stenoses of the phantom. This suggested that for analysis of clinical coronary angiograms it would be more feasible to perform densitometric studies from unsubtracted images. The acquisition of digital images in an unsubtracted mode permits panning with the image intensifier during coronary angiography. If angiography is obtained without motion, then digital subtraction can be applied optionally during postprocessing to enhance contrast. The method for calculating the in-

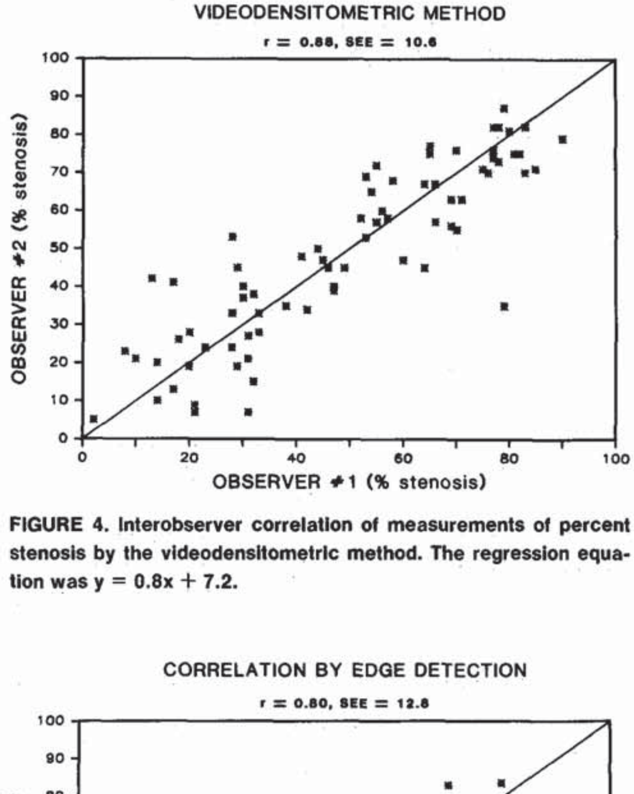

FIGURE 4. Interobserver correlation of measurements of percent stenosis by the videodensitometric method. The regression equation was $y = 0.8x + 7.2$.

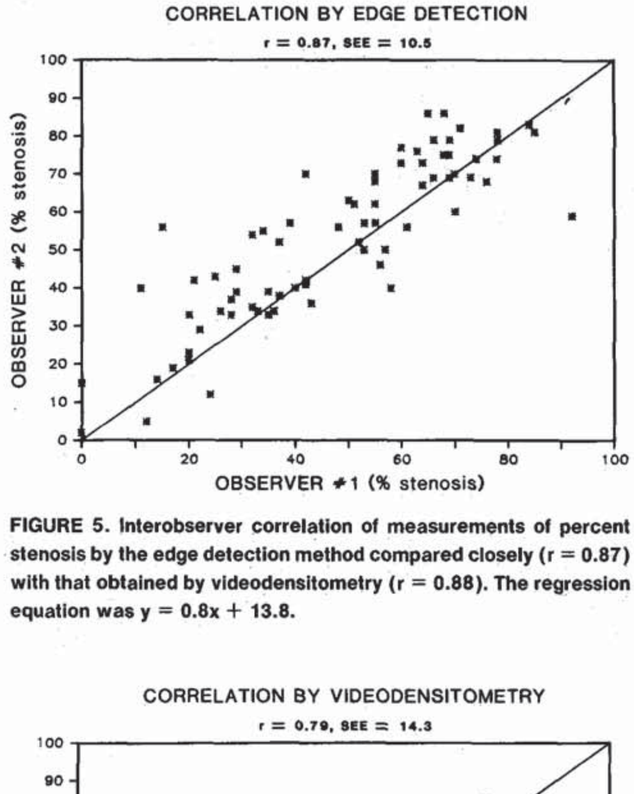

FIGURE 5. Interobserver correlation of measurements of percent stenosis by the edge detection method compared closely ($r = 0.87$) with that obtained by videodensitometry ($r = 0.88$). The regression equation was $y = 0.8x + 13.8$.

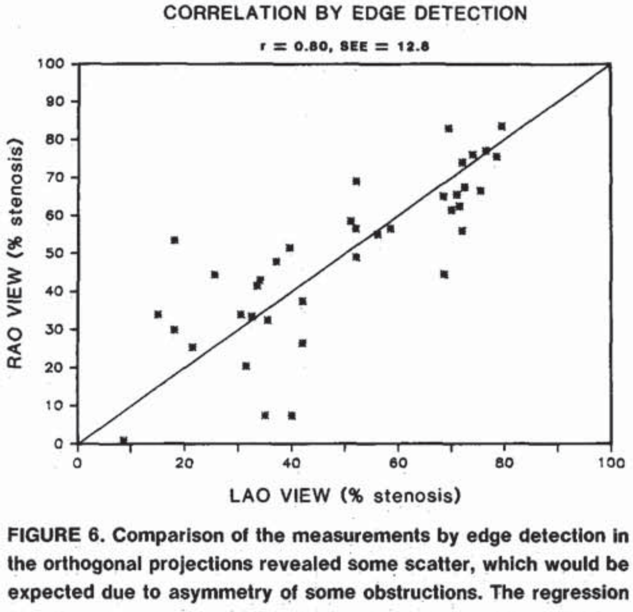

FIGURE 6. Comparison of the measurements by edge detection in the orthogonal projections revealed some scatter, which would be expected due to asymmetry of some obstructions. The regression equation was $y = 0.8x + 10.1$. LAO = left anterior oblique; RAO = right anterior oblique.

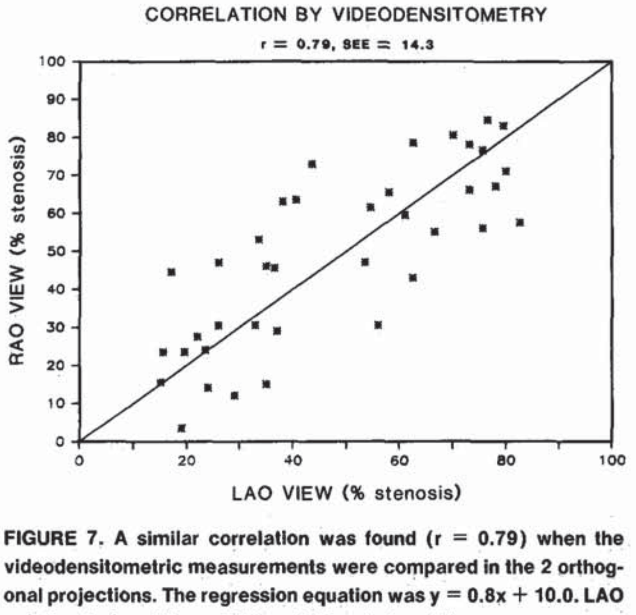

FIGURE 7. A similar correlation was found ($r = 0.79$) when the videodensitometric measurements were compared in the 2 orthogonal projections. The regression equation was $y = 0.8x + 10.0$. LAO = left anterior oblique; RAO = right anterior oblique.

terpolated background was also simplified by the finding that the assumption of a linear change in background densities across the vessel width gave similar results to more complicated estimates using polynomial curve fitting.

Because percent stenosis is a relative number that is strongly influenced by where the normal segment of a coronary artery is chosen, the absolute minimum luminal diameter may be a more appropriate method to compare the results of quantitative analysis studies. The third phantom study demonstrated that minimum luminal diameter could be readily calculated from digitally acquired images either by standard edge detection or in combination with the densitometric algorithm.

The densitometric method has an advantage: The observer does not need to define exactly the boundary of the vessel. The fourth phantom model demonstrated that the densitometric method was more accurate compared with the edge detection method when the boundary of the phantom lumen was superimposed and not readily visualized. The phantom study documented that the densitometric method is independent of irregular shapes that would be misleading with edge detection methods. This observation may be important when there is a disparity between the 2 measurement techniques in clinical studies, and it is not clear which measurement represents the true luminal size.

When the algorithm was applied to clinical digital angiograms in patients who are undergoing angioplasty, it was found that there was a close correlation between the edge detection and videodensitometric methods for calculating percent diameter stenosis. There were also close correlations between 2 independent observers for calculating percent stenosis using either of the 2 techniques. The close interobserver correlations may be due in part to the attention paid to ensure that both observers measured the same normal and stenotic segments.

The usual method of quantifying stenoses by percent diameter narrowing is dependent on the size of an apparently normal segment. However, the functionally significant hemodynamic measurement, resistance to flow, is proportional to lesion length and viscosity but varies inversely with the fourth power of the absolute luminal diameter.[17] A 50% diameter stenosis of a 2-mm vessel has a significantly higher resistance to flow than a 50% diameter stenosis of a 4-mm vessel. Therefore, absolute minimum luminal diameter or area may be a more reliable method of stenosis quantitation.[18] In this series of patients who were undergoing PTCA for symptomatic angina, the mean stenotic luminal diameter was 1.0 ± 0.5 mm before PTCA and 2.4 ± 0.5 mm after PTCA. Therefore, approximately a 2½-fold increase in luminal diameter occurred. These calculated dimensions are consistent with the quantitative study from 35-mm film of McMahon et al[19]; in their group of 10 patients with unstable angina without myocardial infarction, the mean minimum luminal diameter was 0.9 mm, while in 5 other patients who had evidence of non-Q-wave myocardial infarction during their unstable angina syndrome, the mean minimum luminal diameter was 0.6 mm. Minimum luminal diameter is also readily obtainable by a densitometric technique that is independent of luminal geometry and may be a preferable method for measuring the severity of coronary stenoses.

As suggested by the fourth phantom model study, the benefit of the videodensitometric method for calculating stenosis dimensions independently of luminal irregularities would be expected to be helpful after PTCA when luminal irregularities with unclear boundaries are observed. An initial hypothesis, therefore, was that videodensitometric measurements from orthogonal projections after PTCA would correlate more closely than measurements by edge detection. However, it was found that the correlation between the 2 orthogonal angiographic projections for both techniques was similar both before and after PTCA. There are several possible explanations for this, including the effects of the method of x-ray acquisition on densitometric calculations, overlap of vessels, foreshortening of the normal or stenotic segment in 1 of the projections or the possibility that most of the lesions were nearly circular in cross section even after PTCA.

Digital acquisition provides immediate recall of coronary angiograms during PTCA. Reproducible and dimensionally precise measurements can be made at the area of stenosis within 2 minutes of acquisition. The densitometric measurements are linearly proportional to the digital pixel depth, unlike film-based systems, in which densitometry is limited to the linear portion of the film characteristic curve. Edge detection or videodensitometric techniques can be used with comparable results. However, in individual cases, discrepancy between the 2 techniques implies that there may be adventitial dissections. A more complete clinical assessment of stenosis severity requires both a quantitative angiographic analysis as well as a functional assessment.

Acknowledgment: We thank Ellen Mansour, BA, Eunice Henderson, LVN, Jim Paynter, CPT, and Carol DeBoer, RN, for their assistance in the performance of this study.

References

1. Gruentzig AR. *Technique for percutaneous transluminal coronary angioplasty. In: Hurst JW, ed. The Heart. New York: McGraw-Hill, 1982:1904-1908.*

2. Kent KM, Bentivoglio LG, Block PC, Cowley MJ, Dorros G, Gosselin AJ, Gruntzig A, Myler RK, Simpson J, Stertzer SH, Williams DO, Fisher L, Gillespie MJ, Detre K, Kelsey S, Mullin SM, Mock MB. *Percutaneous transluminal coronary angioplasty: report from the registry of the National Heart, Lung, and Blood Institute. Am J Cardiol 1982;49:2011-2020.*

3. Zir LM, Miller SW, Dinsmore RE, Gilbert JP, Harthorne JW. *Interobserver variability in coronary angiography. Circulation 1976;53:627-632.*

4. DeRouen TA, Murray JA, Owen W. *Variability in the analysis of coronary arteriograms. Circulation 1977;55:324-328.*

5. Detre KM, Wright E, Murphy ML, Takaro T. *Observer agreement in evaluating coronary angiograms. Circulation 1975;52:979-986.*

6. Sanmarco ME, Brooks SH, Blankenhorn MD. *Reproducibility of a consensus panel in the interpretation of coronary angiograms. Am Heart J 1978; 96:430-437.*

7. Trask N, Califf RM, Conley MJ, Kong Y, Peter R, Lee KL, Hackel DB, Wagner GS. *Accuracy and interobserver variability of coronary cineangiography: a comparison with postmortem evaluation. JACC 1984;3:1145-1154.*

8. Vlodaver Z, Frech R, Van Tassel RA, Edwards JE. *Correlation of the antemortem coronary arteriogram and the postmortem specimen. Circulation 1973;47:162–169.*

9. Leu HJ, Grüntzig A. *Histopathological aspect of transluminal recanalization: percutaneous vascular recanalization. In: Zeitler E, Grüntzig AR, Schoop W, eds. Heidelberg: Springer-Verlag OHG, 1978.*

10. Baughman KL, Pasternak RC, Fallon JT, Block PC. *Transluminal coronary angioplasty of postmortem human hearts. Am J Cardiol 1981;48:1044.*

11. Trenholm BG, Winter DA, Mymin D, Lansdown EL. *Computer determination of left ventricular volume using videodensitometry. Med Biol Eng 1972;10:163–173.*

12. Sandor T, Als AV, Paulin S. *Cine-densitometric measurement of coronary arterial stenoses. Cathet Cardiovasc Diagn 1979;5:229–245.*

13. Booman F, Reiber JHC, Gerbrands JJ, Slager CJ, Schuurbiers JCH, Meester GT. *Quantitative analysis of coronary occlusions from coronary cineangiograms. Comput Cardiol 1979;177–180.*

14. Nichols AB, Gabrieli CFO, Fenoglio JJ, Esser PD. *Quantification of relative coronary arterial stenosis by cinevideodensitometric analysis of coronary arteriograms. Circulation 1984;69:512–522.*

15. Tobis J, Nalcioglu O, Iseri L, Johnston WD, Roeck W, Castleman E, Bauer B, Montelli S, Henry WL. *Detection and quantitation of coronary artery stenoses from digital subtraction angiograms compared with 35-millimeter film cineangiograms. Am J Cardiol 1984;54:489–496.*

16. Tobis J, Nalcioglu O, Seibert A, Johnston WD, Henry WL. *Measurement of left ventricular ejection fraction by videodensitometric analysis of digital subtraction angiograms. Am J Cardiol 1983;52:871–875.*

17. Brown BG, Bolson E, Firmer M, Dodge HT. *Estimation of dimensions, hemodynamic resistance, and atheroma mass of coronary artery lesions using the arteriogram and digital computation. Circulation 1977;55:329–337.*

18. Brown BG, Bolson EL, Dodge HT. *Arteriographic assessment of coronary atherosclerosis: review of current methods, their limitations, and clinical applications. Atheriosclerosis 1982;2:2–15.*

19. McMahon MM, Brown BG, Cukingnan R, Rolett EL, Bolson E, Frimer M, Dodge HT. *Quantitative coronary angiography: measurement of the "clinical" stenosis in patients with unstable angina and single-vessel disease without collaterals. Circulation 1979;60:106–113.*