METHODS

Patterns in Visual Interpretation of Coronary Arteriograms as Detected by Quantitative Coronary Arteriography

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In part 1 of a three-part study, 14 novice readers and 6 experienced cardiologists interpreted phantom images of known stenosis severity. No difference between the interpretations of experienced and novice readers was detectable. Visual estimates of "moderately" severe stenosis were 30% higher than actual percent diameter stenosis.

In part 2 of the study, visual interpretation of percent diameter stenosis from 212 stenoses on 241 arteriograms was compared with quantitative coronary arteriographic assessment. The visual analysis overestimated disease severity in arteries with ≥50% diameter stenosis (except for right coronary lesions) and underestimated severity in all arteries with <50% diameter stenosis. Of the 241 arteriograms, 40 had quantitative and visual analysis of all three coronary arteries for assessment of significant disease. In only 62% of the cases did visual and quantitative methods agree on the presence of severe disease; visual estimates diagnosed significantly ($p < 0.05$) more three-vessel disease.

In part 3 of the study, comparison of percent diameter stenosis by visual estimate with quantitative coronary arteriographic assessment before and after balloon angioplasty of 38 stenoses showed that visual interpretation significantly ($p < 0.001$) overestimated initial lesion severity and underestimated stenosis severity after angioplasty.

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Most studies to date have used visual interpretation of coronary arteriograms as the reference standard for determining the presence or absence of significant coronary artery disease. Several investigators (1–3) have demonstrated significant interobserver and intraobserver variability in visual estimates of percent diameter stenosis. A recent report (4) indicates that this variability may not be related to observer experience. These studies from various geographic regions suggest that such variability is not due to regional or institutional differences in visual reporting of arteriograms, but may be related to basic characteristics of visual interpretations of arteriograms. No previous investigation has determined whether there are patterns in visual reporting of percent diameter stenosis and what the clinical implications might be.

The accuracy of automated quantitative coronary arteriography has been validated in three independent experimental studies (5–7) and demonstrated to be applicable in humans (8). Automated quantitative coronary arteriography provides a unique tool for studying patterns in visual reporting of stenosis from arteriograms. Comparing quantitative coronary arteriographic measures of percent diameter stenosis with visual estimates of percent diameter stenosis, this study addresses three related questions: 1) What role does experience play in the interpretation of percent diameter stenosis? 2) What is the average error made by visual estimation of percent diameter stenosis from coronary arteriograms and is there a pattern to the error? 3) What are the clinical implications of these errors or patterns? For example, how many patients are classified as having significant three-vessel coronary artery disease by visual interpretation as compared with quantitative coronary arteriography and to what extent are the severity of stenosis before angioplasty and the postangioplasty benefit misjudged by visual interpretation in comparison with quantitative coronary arteriographic analysis.

Methods

Experienced versus novice readers of coronary arteriograms. Six experienced cardiologists and 14 cardiology fellows and members of the Department of Cardiology voluntarily participated in the reading of phantom images. Each individual read in a blinded manner the apparent visual severity of the stenosis on six cine X-ray films of stenosis phantoms of known percent diameter narrowing (17% to 83%) filled with 100% contrast scattering medium.

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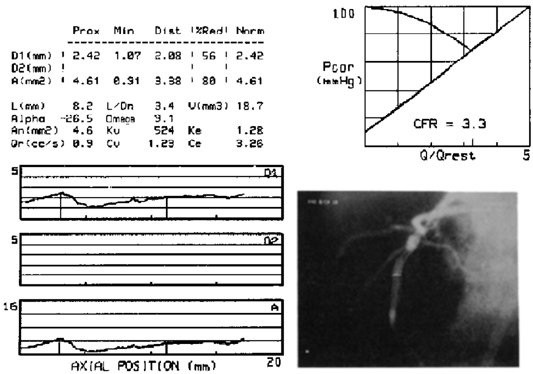

Figure 1. Automated quantitative coronary arteriography in a subject with a 56% diameter stenosis of a diagonal branch of the left anterior descending coronary artery. The artery is bordered by a **broken line,** which defines the region of maximal stenosis. Other information shown includes an 80% reduction in area, entry (alpha) and exit (omega) angles to and from the lesion, and the coronary flow reserve. A = cross-luminal area; An = normal cross-sectional area; CFR = calculated coronary (stenosis) flow reserve; Ce and Ke = momentum coefficient losses based on alpha and omega; Cv and Kv = coefficients of viscosity losses secondary to geometry of stenosis; D_1 and D_2 = orthogonal single-plane diameters; Dist = distal; L = lesion length; L/Dn = length/diameter ratio; Min = minimal diameter; Norm = normal coronary segment; Pcor = coronary perfusion pressure; %Red = percent reduction; Prox = proximal segment; Q/Qrest = ratio of maximal to rest flow or coronary flow reserve; Qr = rest flow; V = intraluminal volume in the stenotic segment.

Coronary arteriograms. Two hundred twelve arterial segments were prospectively collected on 241 arteriograms. Stenosis severity by visual interpretation of biplane coronary arteriograms was determined by the physician performing the catheterization procedure in each case (standard clinical practice). The lesions were defined by percent diameter stenosis, ≥50% stenosis and (analyzed separately) ≥70% stenosis defined the presence of significant disease. All lesions were assessed without knowledge of other data by the cardiologist performing the catheterization procedure and were graded by at least one of us (more than one if any doubt existed) to assure correct assignment and subsequent analysis by quantitative coronary arteriography.

In 40 of the 241 coronary arteriograms all three coronary arteries were compared by both the visual and quantitative techniques; in the remaining arteriograms, either one or two vessels were analyzed by both methods. In these remaining cases, the original arteriographer did not report percent diameter stenosis of the remaining coronary arteries. Only the most severe stenosis for any coronary artery was analyzed. A total of 212 coronary artery stenoses from the 241 arteriograms were compared by each method.

Automated quantitative coronary arteriography. Automated quantitative coronary arteriography was performed on the same 241 catheterization films, studying the lesions identified by the cardiologist performing the coronary arteriogram. Multiple simultaneous biplane views were obtained after contrast injection with standard doses of either Hypaque or Isovue (3 to 10 ml). A Philips Poly Diagnost C/Lateral ARC system was used for imaging. The X-ray tube was a SRC 120 ceramic tube assembly with a 0.3- to 0.8-mm focal spot, operating at 4 to 6-ms exposures at 150 keV. The resolution of the cine system was 4 to 5 line pairs/mm, with both pincushion and magnification correction carried out in the analysis according to the methods of Brown et al. (9). Selected end-diastolic cine frames were digitized by a Spatial Data System frame grabber (640 by 480 matrix) with optical magnification to obtain a spatial resolution of approximately 0.1 mm/pixel. Subsequent image processing (border recognition, magnification correction and stenosis morphology determinations) was performed with previously validated software (10–13). Hard copy reports were generated on a Tektronics 4207 graphics terminal. Lesions with ≥50% and ≥70% diameter stenosis were used to define significant lesions for this study. An example of an automated quantitative coronary arteriogram is demonstrated in Figure 1.

Angioplasty evaluation. Thirty-eight stenotic lesions from 30 subjects were analyzed by both visual estimates of percent diameter stenosis and quantitative coronary arteriographically determined percent diameter stenosis. The visual reporting of lesion severity was by consensus agreement of two angiographers.

Statistical methods. Concordance between visual and quantitative methods was analyzed. Chi-square analysis was used to determine if differences existed between the number of vessels considered significantly diseased (≥50% or ≥70%

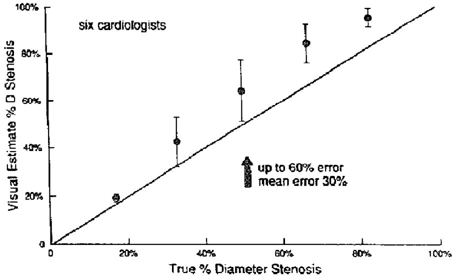

Figure 2. Visual estimates of phantom percent diameter (D) stenosis reported by six cardiologists for six phantom images. The visual estimates of "moderately" severe stenosis were 30% greater than the true percent diameter stenosis, with individual errors of up to 60%.

diameter stenosis) by visual and quantitative methods. Differences between the mean percent diameter stenosis by visual and quantitative methods were compared by two-tailed *t* tests. F ratio testing was used to detect differences in variance. Frequency histograms were used to demonstrate differences between results obtained by quantitative and visual methods. Additional comparison was made by graphing visual diameter stenosis against quantitative diameter stenosis for both the phantoms and the arteriograms.

Results

The six phantom images. When results of percent diameter stenosis for the six phantom images were reported, experienced cardiologists and novice readers reported similar results (p = NS), with a highly positive correlation (r = 0.998). Figure 2 shows the reported results for phantom images by the experienced cardiologists. For "moderately" severe lesions ranging from 40% to 60% stenosis, visual estimates were 30% higher than the true percent diameter stenosis, with individual visual errors ranging up to 60% unrelated to observer experience. Two distinct patterns of visual readings were detected (Fig. 3). Cardiologist B represents a frequent characteristic of interpreting stenosis severity, in which readers "saw" percent area stenosis and not percent diameter narrowing. This pattern was manifested by better agreement with the true percent area narrowing than with true percent diameter narrowing. However, readers experienced in automated quantitative coronary arteriography (cardiologist A) and trained in "seeing" arterial borders on arteriograms visually estimated percent diameter narrowing quite accurately in comparison with true percent diameter narrowing.

Arteriograms with three coronary arteries involved (Tables 1 and 2). Of the 40 arteriograms in which all three coronary arteries were analyzed by both visual and quantitative methods, there was agreement in only 27 (67%) of the cases as to the number of significantly (≥50% diameter stenosis)

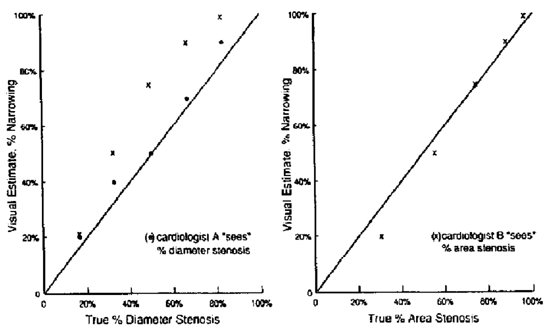

Figure 3. Two patterns of stenosis detection. Cardiologist A (left panel) was trained in border recognition by quantitative coronary arteriography. Results are similar to the actual percent diameter stenosis. Cardiologist B (right panel) had no prior training with quantitative coronary arteriography and read percent area stenosis, not percent diameter.

JACC Vol. 18, No. 4
October 1991:945–51

Table 1. Concordance Between Visual and Quantitative Analysis of Coronary Arteriograms

	Visual and QCA Agree	Visual and QCA Disagree	Concordance (%)
All three arteries	25	15	62
Right coronary artery	33	7	82
Left anterior descending artery	35	5	87
Left circumflex artery	34	6	85

QCA = quantitative coronary arteriography.

diseased vessels. However, in two of these cases in which single-vessel disease was reported, the visual and quantitative methods did not agree on which vessel was significantly diseased. Therefore, in only 25 (62%) of the 40 cases did both methods agree on the presence or absence of significant disease in all three coronary arteries (Table 1). The two methods agreed in 82%, 85% and 87% of instances on the presence of disease in, respectively, the right, the left circumflex and the left anterior descending coronary artery.

The number of cases in which no significant stenosis was detected or in which only one coronary artery was considered significantly diseased was the same for visual and quantitative analysis (p = NS) (Table 2). Each method reported two-vessel disease in 25% of subjects (p = NS). However, the visual method reported more patients with significant (≥50% diameter stenosis) three-vessel coronary artery disease than did quantitative analysis ($p < 0.05$).

Analysis of 212 stenotic segments. When all 212 coronary artery segments were compared by the two methods, there was no statistical difference between the mean percent diameter stenosis (Table 3); however, F ratio analysis demonstrated a greater visual variance ($p < 0.01$). Figure 4 shows the frequency histograms for both quantitative and visual reporting of percent diameter stenosis from the same 212 stenotic segments. Frequency histograms were reported for 10% intervals because the visual reporting of percent diameter stenosis was almost always expressed in 10% increments until percent diameter stenosis exceeded 90%. The two approaches gave different results for the same sample. The quantitative method demonstrated a more gaussian distribution of disease, which suggests that the sample size was adequate to represent the population as a whole. The visual method revealed a trimodal grouping of data (0%, 40% to 60%, and 100%), which can be seen both on the frequency histogram (Fig. 4B) and in the comparison graph (Fig. 5). Figure 5 compares percent diameter stenosis by visual versus quantitative reporting. There is a plateau in the relation of stenosis severity by visual estimates compared with quantitative estimates in the severity range from 20% to 80% that is seen visually as 40% to 60% diameter stenosis. This relation between quantitative and visual estimates of severity held true for the left anterior descending, left circumflex and right coronary arteries.

Nonsignificant versus significant stenosis. Table 3 shows the severity classification based on visual compared with quantitative estimates for lesions considered nonsignificant (<50%) and significant (≥50%) by arterial distribution. Visual estimate of disease overestimated the extent of significant disease. This overestimation was statistically significant for the left anterior descending ($p < 0.05$) and circumflex ($p < 0.005$) arteries. Additionally, visual variance was significantly greater for the left circumflex artery ($p < 0.01$). Furthermore, visual estimates of disease always underestimated nonsignificant disease. This difference was statistically significant for all three coronary arteries ($p < 0.001$).

Stenoses ≥70%. A comparable analysis was carried out for a threshold of ≥70% or <70% diameter stenosis as the criterion of significant coronary artery disease. No statistical difference was detected between the visual and quantitative approaches for stenoses with ≥70% diameter narrowing. Visual estimates of disease underestimated the extent of stenosis for lesions with <70% diameter stenosis. This underestimation was statistically significant for the right ($p < 0.025$), left anterior descending and left circumflex ($p < 0.001$) coronary arteries.

Stenoses before and after angioplasty. Table 4 shows stenosis severity by visual and quantitative estimates from coronary arteriograms obtained before and after angioplasty of 38 stenoses. The results are significantly different ($p < 0.001$), demonstrating the visual overestimation of lesions with ≥50% diameter stenosis and underestimation of lesions with <50% diameter stenosis.

Table 2. Comparison of the Number of Vessels With ≥50% Diameter Stenosis as Determined by Visual and Quantitative Analysis of Coronary Arteriograms

	No. of Vessels With >50% Diameter Stenosis			
	0	1	2	3
Visual	7	12	10	11
QCA	9	15	10	6
p value	NS	NS	NS	<0.05

QCA = quantitative coronary arteriography.

Discussion

Errors in visual interpretation of coronary stenoses. Problems in visual estimation of disease from coronary arteriograms have been reported since the mid 1970s (1–3). Recently, Beauman and Vogel (4) suggested that these problems may not be related to observer experience. Our phantom study demonstrated a high correlation ($r = 0.998$) between reported results from experienced cardiologists and novice readers. This agreement would suggest that errors in visual reporting are due to a characteristic trend or pattern in visual interpretations of coronary arteriograms unrelated to observer experience. Furthermore, these errors are not

Table 3. Comparison of the Severity of Disease by Visual and Qualitative Analysis of Coronary Arteriograms

Vessel/Method	No. of Segments	Mean and p Value		No. of Segments	Mean and p Value	
		All Disease				
All three						
Visual	212	54.88	NS			
QCA	212	52.73				
		Disease <50%			Disease >50%	
RCA						
Visual	22	16.36	p < 0.001	45	78.53	NS
QCA	34	34.53		33	73.82	
LAD						
Visual	25	18.80	p < 0.001	55	77.94	p < 0.05
QCA	25	34.56		55	70.67	
LCx						
Visual	33	14.54	p < 0.001	32	78.22	p < 0.005
QCA	43	31.51		22	66.50	
		Disease <70%			Disease >70%	
RCA						
Visual	38	32.37	p < 0.025	29	91.86	NS
QCA	54	43.81		13	95.69	
LAD						
Visual	43	33.02	p < 0.001	37	90.19	NS
QCA	57	47.32		23	89.30	
LCx						
Visual	40	21.25	p < 0.001	25	85.32	NS
QCA	60	39.75		5	86.60	

LAD = left anterior descending coronary artery; LCx = left circumflex coronary artery; QCA = quantitative coronary arteriography; RCA = right coronary artery.

limited to single-plane interpretations of coronary arteriograms because 50% of the studies involved biplane images. Because the clinical interpretation of lesions by the cardiologist performing the catheterization procedure was made using the same views as those analyzed by quantitative coronary arteriography, errors cannot be attributable to the angle of reference to the lesion. One of the characteristic errors of visual interpretation is shown in Figure 3 as the tendency for many readers to "see" percent area stenosis rather than percent diameter stenosis. However, as cardiologist A in Figure 3 demonstrates, experience with border recognition training can result in more accurate visual estimates of "true" percent diameter stenosis.

Diagnosis of triple-vessel coronary disease. The results obtained by analysis of the subgroup of patients in whom all three coronary arteries were examined by visual interpretation and quantitative methods provided additional insight into how the severity of disease on coronary arteriograms is reported. There was agreement between visual estimates of percent diameter stenosis and quantitative estimates in only slightly >50% of the cases. This study demonstrated a statistically larger number of patients considered by visual, as compared with quantitative, assessment to have three-vessel coronary artery disease. This larger number may reflect a bias that significant disease in one or two coronary arteries is associated with significant disease in the third. Patients frequently are referred for coronary artery bypass operations rather than medical management on the basis of a diagnosis of three-vessel disease.

Variability in visual estimates of percent diameter stenosis. When all 212 lesions were compared, a trimodal pattern for the visual reporting of percent diameter stenosis was detected. The qualitative visual grouping of data reported lesions as "mild" (0% to 10% stenosis), "moderate" (40% to 60% stenosis) and "severe" (90% to 100% stenosis). Visual estimates of percent diameter stenosis were associated with significantly greater variance ($p < 0.01$). Although previous studies (1–4) have alluded to this variability in visual inter-

JACC Vol. 18, No. 4
October 1991:945–51

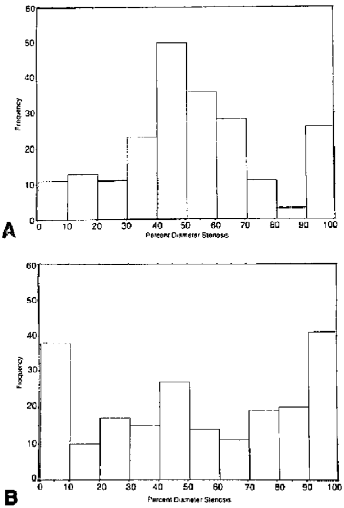

Figure 4. A, Frequency histogram of percent diameter stenosis as measured by quantitative coronary arteriography. (A) and the visual method (B). A, The bar graph shows a gaussian type distribution of disease over the 212 coronary artery segments studied. A significant number of arteries are totally occluded, reflecting the high prevalence of disease in the patients examined. B, The bar graph represents three distinct peaks at 0%, 50% and 100% diameter stenosis. Detection of disease between the peaks is less frequent and is found at 10% intervals. Visual reporting of percent diameter stenosis is trimodal and not gaussian.

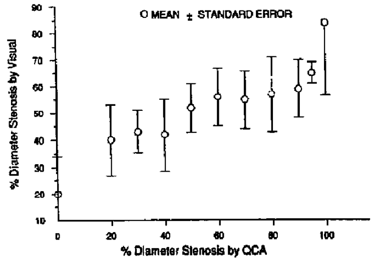

Figure 5. Percent diameter stenosis by the visual method plotted against percent diameter stenosis by quantitative coronary arteriography (QCA). There is good agreement between the two methods at 0% and 100% diameter stenosis. However, visual estimates tend to cluster disease between 40% and 60% (50% peak) when quantitative coronary arteriography (QCA) reports percent diameter stenosis ranging from 20% to 80%.

pretation of percent diameter stenosis, our study demonstrates that it cannot be explained by inexperience or angle of reference. The clustering of data into mild, moderate and severe categories suggests that a nonverbal mode of training by example has been occurring in the education of cardiology fellows without objective comparison or training in proper visual interpretation of percent diameter narrowing.

Mild versus severe coronary lesions. Finally, we observed a significant overestimation of percent diameter stenosis by the visual method when quantitative arteriographically assessed stenosis was ≥50% and visual underestimation of stenosis severity when diameter stenosis by quantitative assessment was <50%. No visual overestimation of stenosis severity was detected for lesions with ≥70% diameter stenosis. This observation may partially reflect the smaller number of lesions that were included in this analysis. Additionally, assuming an average diameter of 3 mm for a coronary artery, the difference between 70% and 100% diameter narrowing reflects only a 0.9-mm difference, which is not readily visually observed. Visual underestimation of stenosis severity was also found when stenosis severity by quantitative analysis was <70%.

Thus, "severe" lesions are overestimated and "mild" lesions underestimated. An example of the important clinical ramifications of this observation is demonstrated by the angioplasty data, in which the visual scoring significantly overestimated the improvement in stenosis as a result of the intervention. These data suggest that the current visual approach does not provide the accuracy needed to detect true changes resulting from angioplasty. Some of the problems with restenosis may be related to initial failure not appreciated by the current visual estimates.

Conclusions. The results obtained from the phantom and arteriographic studies suggest the following observations

Table 4. Comparison of Reported Percent Diameter Stenosis by Visual Interpretation and Automated Quantitative Coronary Arteriography (QCA) of 38 Lesions Before and After Angioplasty

	Before Angioplasty	After Angioplasty	p Value
Visual % stenosis	85 ± 12	30 ± 15	< 0.001
Automated QCA % stenosis	68 ± 10	49 ± 12	< 0.001
QCA % area stenosis	86 ± 8	67 ± 13	< 0.001
QCA minimal diameter (mm)	1.1 ± 0.4	1.7 ± 0.4	< 0.001
QCA minimal area (mm)	1.1 ± 0.7	2.5 ± 1.1	< 0.001
QCA stenosis flow reserve	2.1 ± 1	3.7 ± 0.7	< 0.001

that have not been previously reported: 1) visual estimates of stenosis severity tend to aggregate into qualitatively "mild," "moderate" and "severe" categories; 2) visual methods overestimate the number of significantly stenosed vessels; 3) visual estimates of stenosis severity for moderate stenosis are on average 30% greater than the percent diameter assessed by the quantitative method; and 4) most readers "see" percent area stenosis, but with experience in border recognition can accurately assess percent diameter stenosis.

Coronary angiography has been a reference standard because of its unique ability to provide direct information about coronary luminal anatomy. The increased resolution and objectivity of automated quantitative coronary arteriography provide substantial improvements in the interpretation of coronary arteriograms. Quantitative coronary arteriography can provide the accuracy and reproducibility that are particularly necessary to detect changes in coronary anatomy associated with risk factor modification or resulting from angioplasty. Visual estimates of percent diameter stenosis follow characteristic patterns that can be altered with appropriate training to reduce some of the error encountered in clinical practice.

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