Comparison of Simultaneously Performed Digital and Film-Based Angiography in Assessment of Coronary Artery Disease

John C. Gurley, MD, Steven E. Nissen, MD, David C. Booth, MD, Michael Harrison, MD, Paul Grayburn, MD, Jonathan L. Elion, and Anthony N. DeMaria, MD

This study compared digital angiography (Digital) to conventional cineangiography (Cine) for the diagnosis and quantification of coronary artery disease. Digital and Cine were obtained simultaneously under identical radiographic conditions during routine coronary arteriography. Using visual inspection and manual calipers, four independent observers identified 131 stenoses in 18 patients with multivessel coronary disease. There was no difference in interobserver variability between Digital and Cine during multiple subgroup analyses. Overall, Digital yielded significantly greater estimates of stenosis severity than did either of two separate Cine observations ($p<0.0001$; average difference, 6.25%), but the differences fell below the level of statistical significance when only the group of stenoses 50% or greater were considered. Digital and Cine correlated well for the assessment of stenosis severity ($r=0.88$), but linear regression comparisons of multiple subgroups consistently indicated modest overestimation of Cine by Digital. Smaller vessels, branch vessels, and mild lesions increased the likelihood of overestimation by Digital. Digital was highly sensitive for identification of clinically relevant stenoses, but less specific and less predictive than a second observation of Cine. Our results indicate that Digital and Cine are not interchangeable imaging techniques and that potential differences must be considered when Digital is used for clinical decision making. (Circulation 1988;78:1411-1420)

Recent advances in computer technology have made coronary imaging by digital techniques a potential alternative to film-based angiography. By substituting a video camera and computer for conventional cineangiographic equipment, coronary arteriograms can be recorded electronically and viewed on a television monitor. Digital arteriograms appear very similar to film cineangiograms but have the advantage of immediate availability for interpretation. Furthermore, the digital format facilitates postacquisition image processing and analysis such as magnification, edge enhancement, and coronary flow reserve determination. The opportunity for immediate playback of high-quality images makes digital angiography particularly attractive in the field of percutaneous transluminal coronary angioplasty (PTCA). In this application, the visual interpretation of digital arteriograms at the time of catheterization may assist in clinical decision making, potentially obviating the need for separate diagnostic and interventional procedures. However, because small variations in the assessment of stenosis severity may influence the decision to perform PTCA, it is essential to know whether digital and cine imaging yield identical diagnostic and quantitative information.

Despite the increasing popularity of digital coronary arteriography, it is unknown whether currently available digital methods are equivalent to conventional cineangiography in the visual assessment of coronary stenoses. Previous investigations have compared standard cineangiograms with videotaped digital images that were obtained during separate procedures with different radiographic techniques and that were subsequently subjected to subtraction and edge enhancement processing. There has been no comparative study of digital and cine coronary arte-
angiography performed under identical imaging conditions. The objective of this study, therefore, was to compare simultaneously acquired digital and cine coronary arteriograms obtained under precisely identical radiographic conditions with state-of-the-art equipment for both imaging modalities.

Patients and Methods

Radiographic Technique

All arteriography was performed with a commercially available radiographic unit (LU/C, MPX 100 generator, HTC-II X-ray tube, L500 image intensifier, General Electric, Milwaukee, Wisconsin). The radiographic tubes used a 0.9-mm nominal focal spot size, and the image intensifier offered three fields of view: 22, 15, and 10 cm. Coronary imaging was performed at 30 frames/sec during manual injections of 5-10 ml MD-76 iohexol contrast (Renografin-76, E.R. Squibb & Sons, Princeton, New Jersey). Nearby all arteriograms used the 15-cm field of view, whereas the 10-cm mode was selected on occasion. Automatic brightness compensation was achieved by computer-controlled generators that adjusted the tube potential from 70 to 100 kVp and the pulse width up to 7 msec. The nominal x-ray exposure to the image intensifier was 30 μR/frame in the 15-cm field of view and 50 μR/frame in the 10-cm field of view.

The choice and number of radiographic projections, contrast injection technique, collimation, field of view, and filming technique were selected by the operator with the sole aim of obtaining a complete diagnostic study for clinical purposes. The operators performing coronary arteriography were unaware of the simultaneous digital and cine imaging for the purpose of this study.

Parallel Image Acquisition

The light output of the image intensifier was divided with an optical beamsplitter; 85% was directed to the cine camera and 10% to the video camera (Figure 1). Each x-ray pulse, therefore, produced a simultaneous, identical cine and digital image frame. There was no possibility for variation in radiographic technique, contrast dose, heart position, projection, or operator technique between the two imaging modalities.

Cineangiographic Technique

Cineangiograms were obtained on conventional 35-mm film (Vari-Cath, Vari-X, Irvine, California) with 93% underframing (Figure 2, top panel). Processing was performed according to the manufacturer’s specifications and quality control standards, and the film was developed to produce an average gradient of 1.8. The images were viewed in a darkened room with a rotating prism projector (Tagarno-35, Horsens, Denmark) that provided a continuous range of film speeds from 0 to 80 frames/sec forward and reverse. Coronary stenoses were measured from still frames selected by each observer.

Digital Technique

Digital angiography was performed with a standard commercial computer device, the DF5000 (General Electric). A low-lag, 525-line, progressive scan video camera was focused on the image intensifier as illustrated in Figure 1. Exact framing on a square screen was used. The analog output of the video camera was low pass–filtered at 5 MHz, then digitized in real time by a 10-bit analog-to-digital converter. The resulting digital data were stored on a 474-megabyte multiple-head hard disk (Fujitsu, San Jose, California) with a 512×512-pixel matrix and an 8-bit gray scale. A linear lookup table relating radiographic density to gray level was used. The resulting pixel density was approximately 3.2 pixels/mm in the 15-cm field of view and 4.8 pixels/mm in the 10-cm field of view.

Playback used a digital scan converter to synthesize RS-170 equivalent interlaced images from the digital matrix. The digital arteriograms were viewed in a darkened room on a 12-in., 525-line television monitor that displayed a circular image of 480×480 pixels (equivalent to the 93% underframed cine image, Figure 2, bottom panel). Two forward speeds (4 and 30 frames/sec) and two reverse speeds (4 and 15 frames/sec) were available during playback. As with conventional cineangiography, still-frame viewing was used during measurement of stenoses. The maximum gray scale window was displayed, and the brightness of the television monitor was adjusted to a comfortable viewing level. Once set, these controls were not adjusted by the observers.
Study Population

One hundred thirty-one coronary lesions in 18 patients undergoing diagnostic left-heart catheterization were examined in this investigation. The 474-megabyte storage capacity of the imaging computer permitted acquisition of 1,500 frames, an amount adequate for a complete set of digital arteriograms from a single patient. Because of limited capacity for archival data storage, however, it was necessary to review the digital arteriograms in the catheterization laboratory and then erase the hard disk before further use. The choice of patients, therefore, was based upon availability of all four observers and adequate free time in the catheterization laboratory. Because of these constraints, patients with multivessel coronary artery disease were used whenever possible.
Image Interpretation

Both the digital and cine images were examined independently by the same four observers, all of whom were experienced in coronary arteriography. The digital images were viewed and interpreted immediately after the catheterization. The cineangiograms were viewed for the first time by each of the four observers a mean interval of 47 days after the catheterization. The same cineangiograms were again viewed by each of the observers after another mean interval of 121 days.

Unrestricted forward, reverse, and still-frame playback was permitted during interpretation of both the digital and cine coronary arteriograms. The observers were asked to locate and quantify all stenotic lesions of at least 25% luminal diameter narrowing. Coronary stenoses were measured directly from the viewing screens with manual calipers and a millimeter ruler. Each observer was permitted to select the angiographic projection and frame of his choice for stenosis measurement. Visual analysis of unprocessed images by experienced angiographers using manual calipers for stenosis measurement was specifically chosen for this study because this method of image analysis remains the nearly universal standard of practice. Although the visual measurement of coronary lesions has limitations, this study was specifically designed to compare digital and cine imaging as currently used by clinicians. The percent diameter stenosis was determined by comparing the maximal focal narrowing of each lesion with the nearest normal-appearing segment of the same vessel. Results were reported to the nearest 5% luminal diameter narrowing.

Data Analysis

The left main, left anterior descending, circumflex and right coronary arteries were considered first-order vessels. Immediate branches of these vessels (diagonals, obtuse marginals, septal perforators, etc.) were considered second-order vessels, and subsequent branches were considered third-order vessels. No vessels higher than the third branching order were reported by any of the observers.

The approximate size of each diseased vessel was determined by measuring the diameter of the normal-appearing artery nearest to each stenosis. These measurements were obtained from the cineangiograms and converted to millimeters with the known catheter diameter as the calibration factor.

For each stenosis, the percent diameter narrowing was determined by four observers. These four values were then averaged to obtain a mean stenosis grade for each lesion. This mean stenosis grade was calculated independently for digital angiography (Digital), for the first cine observation (Cine 1) and for the second cine observation (Cine 2). Differences in mean stenosis severity among Digital, Cine 1, and Cine 2 were evaluated by repeated measures analysis of variance (ANOVA). Significant differences between observations were subsequently evaluated by Student's t test for paired data. The correlation of stenosis severity by Digital and Cine 1 was evaluated by linear regression analysis. The same comparison was also made for two separate observations of cine film (Cine 1 vs. Cine 2). Subgroup analysis by the above statistical techniques was performed based on coronary artery size, vessel branching order, and stenosis severity. The reference group for subdivision according to stenosis severity was Cine 1 (mean of four observers for each lesion).

The standard deviation of the percent stenosis determined by the four observers for each lesion was used as an index of interobserver variability. The standard deviation values for each lesion by Digital, Cine 1, and Cine 2 were compared by ANOVA. Subgroup analyses of the interobserver variability were then performed according to vessel size, vessel order, and stenosis severity. The standard deviation values for all lesions were also averaged to yield the mean interobserver variability for Digital, Cine 1, and Cine 2.

Because the above comparisons indicated overestimation of stenosis severity by Digital, the frequency with which Digital overestimated Cine 1 by at least 15% in mean diameter stenosis was calculated. This calculation was performed for the total group of lesions as well as for smaller subgroups of lesions restricted according to vessel size, branching order, and stenosis severity. Fifteen percent was chosen as the cutoff because this value was approximately one standard deviation of the percent stenosis for the four observers, that is, the amount that could reasonably be attributed to interobserver variability.

The relative sensitivity and specificity of Digital and Cine for the detection of clinically significant stenoses were determined by designating Cine 1 as the standard for comparison. In this analysis, the definition of a clinically significant lesion required at least 50% stenosis (mean of four observers) in a first- or second-order coronary vessel that was at least 2 mm in diameter. The analysis included only definite stenoses, defined as lesions reported by two or more observers on Cine 1. Only discrepancies of at least 15% in mean diameter stenosis were accepted as differences among methods, thereby eliminating the influence of interobserver variability (the interobserver variability was approximately 10% for this subgroup of lesions).

Phantom Vessel Studies

To evaluate the relative accuracy of Digital and Cine, 17 stenoses of varying severity were produced by altering the lumen of plastic models of coronary vessels. The phantom vessels ranged from 0.9 to 4.7 mm diameter and the stenoses from 11% to 81% (mean, 49±22%) lumen diameter narrowing. These stenoses were then imaged superimposed upon a heart-chest phantom that simulated the radiological characteristics of the human thorax. The same radio-
logical technique described above was used, and stenosis measurement and data analysis methods were the same as described for the human studies.

Results

Interobserver Variability

For the entire group of 131 stenoses, the average interobserver variability was 14.7% for Cine 1, 16.9% for Digital, and 16.7% for Cine 2 (Figure 3). The degree of interobserver variability was less when the analysis was restricted to lesions of at least 50% diameter narrowing and to vessels of at least a 2-mm diameter. When only stenoses of 50% or more were considered, the interobserver variability was 12.6% for Cine 1, 12.1% for Digital, and 14.3% for Cine 2. In the subgroup of vessels with a 2-mm diameter and larger, the interobserver variability was 14.2% by Cine 1, 15.3% by Digital, and 15.8% by Cine 2. The lowest variability occurred in the subgroup of 33 lesions meeting both the 2-mm diameter size and 50% or more stenosis severity restrictions (Cine 1=10.4%, Digital=10.1%, Cine 2=10.6%). None of the differences in interobserver variability among imaging methods was statistically significant, either for the entire group of lesions or for any subgroup. Thus, there was no difference in interobserver variability between Digital and Cine.

Comparison of Stenosis Severity

For the total group of 131 lesions, the mean luminal diameter narrowing by Digital was 39.7%. This value was significantly greater than that obtained by Cine 1 (33.5%) or by Cine 2 (33.4%). The differences between Cine 1 and Digital were significant at the 95% confidence level by ANOVA ($F=12.27$; average difference, 6.2%). The differences between Cine 2 and Digital were also significant ($F=12.8$; average difference, 6.3%), but the differences between Cine 1 and Cine 2 were not significant ($F=0.006$; average difference, 0.1%). By the paired $t$ test, the differences between either Cine 1 or Cine 2 and Digital were significant at $p<0.0001$, whereas the differences between Cine 1 and Cine 2 were not significant. When only stenoses of more than 50% were included in the same analysis, the differences between Digital and Cine were no longer statistically significant. Thus, overestimation of stenosis severity by Digital was identified, particularly in the setting of lesions less than 50% luminal diameter narrowing.

The mean severity of individual stenoses by Digital and Cine 1 were compared by linear regression analysis. There was a close correlation between techniques, $r=0.88$ (Figure 4, left panel), but the $y$ intercept in the regression equation indicated overestimation of stenosis severity by Digital ($y=0.86x+10.8$, $SEE=13.7$). Regression equation nearly described a line of identity that passed through the origin. Cine 1, 2, first and second observations, respectively, on cineangiograms.
Furthermore, the fact that slope values were lower for the Cine 1 and Digital comparisons than for the Cine 1 and Cine 2 comparisons indicated that overestimation of stenosis severity by Digital occurred more prominently with lesions of less than 50% diameter narrowing. Because no absolute standard of accuracy exists for the measurement of human coronary stenoses, it was impossible to determine whether Digital or Cine yielded more accurate measurements. The term “overestimation” is used, therefore, in a strictly comparative sense.

Vessel size, branching order, and stenosis severity were each found to influence the overestimation of stenosis severity by Digital (Figure 5). An overestimation of at least 15% (approximately one standard deviation) by Digital occurred 24.5% of the time with stenoses of less than 50%, but only 5.4% of the time with stenoses of 50% or greater. This degree of overestimation was more likely to occur in vessels less than 2 mm in diameter than in larger vessels (31.0% vs. 16.7%) and was also more frequent in branch vessels than first-order vessels (25.7% vs. 11.5%). Therefore, the tendency toward overestimation of stenosis severity by Digital was greatest for low-grade lesions and small vessels.

To evaluate the potential clinical impact of the overestimation of stenosis severity by Digital, the relative ability of Digital and Cine to identify and quantify lesions likely to have significant therapeutic implications was examined. For this purpose, a clinically significant lesion was defined as a stenosis of at least 50% mean diameter narrowing occurring in a first- or second-order coronary vessel that was 2 mm diameter or larger. The mean severity of each stenosis by Cine 1 was arbitrarily chosen as the reference value, and only definite lesions (those seen by at least two observers on Cine 1) were included. A discrepancy of at least 15% diameter narrowing (more than one standard deviation) was required to define a difference from Cine 1. There were 101 definite lesions, 32 of which were 50% or more and 16 of which were 70% or more by Cine 1. Digital identified 31 of the 32 stenoses that were graded as 50% or more by Cine 1, resulting in a sensitivity of 96.9%. However, Digital estimated 50% stenosis for nine additional lesions not so classified by Cine 1, yielding a lower specificity of 87.0% and a positive predictive value of 77.5%. Digital identified all of the 16 lesions that were 70% or more by Cine 1, for a sensitivity of 100%. However, Digital identified three additional lesions 70% or greater, yielding a specificity of 96.5% and a positive predictive value of 84.2%. By comparison, Cine 2 more accurately identified significant stenoses as defined by Cine 1 (Tables 2 and 3). For

![Figure 5](http://circ.ahajournals.org/)

**Figure 5.** Bar graphs of probability of digital coronary angiography overestimation of cineangiography by at least 15% diameter stenosis. Overestimation of this degree is more likely with lower-grade lesions (left panel), with smaller vessels (center panel), and with branch vessels (right panel).

### Table 1. Linear Regression Comparison of Stenosis Severity

<table>
<thead>
<tr>
<th>Cine 1 vs. Digital</th>
<th>Cine 1 vs. Cine 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression equation</td>
<td>SEE</td>
</tr>
<tr>
<td>All lesions</td>
<td>( y = 0.86x + 10.76 )</td>
</tr>
<tr>
<td>Vessels</td>
<td></td>
</tr>
<tr>
<td>( \geq 2 ) mm</td>
<td>( y = 0.87x + 11.02 )</td>
</tr>
<tr>
<td>&lt;2 mm</td>
<td>( y = 0.79x + 10.43 )</td>
</tr>
<tr>
<td>First-order</td>
<td>( y = 0.91x + 10.48 )</td>
</tr>
<tr>
<td>Second- and third-order</td>
<td>( y = 0.77x + 11.60 )</td>
</tr>
</tbody>
</table>

Vessels, first observation of cineangiogram; Cine 2, second observation of cineangiogram; Digital, observation of digital arteriograms; \( y \), Cine 1; \( x \), Digital or Cine 2.

### Table 2. Sensitivity, Specificity, and Predictive Value* in Detection of Stenosis 50% or Greater

<table>
<thead>
<tr>
<th></th>
<th>Digital</th>
<th>Cine 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity (%)</td>
<td>96.9</td>
<td>90.6</td>
</tr>
<tr>
<td>Specificity (%)</td>
<td>87.0</td>
<td>95.7</td>
</tr>
<tr>
<td>Predictive value (positive) (%)</td>
<td>77.5</td>
<td>90.6</td>
</tr>
</tbody>
</table>

Digital, observation of digital arteriograms; Cine 2, second observation of cineangiographic film.

*In regard to first observation of cineangiographic film.
TABLE 3. Sensitivity, Specificity, and Predictive Value* in Detection of Stenosis 70% or Greater

<table>
<thead>
<tr>
<th></th>
<th>Digital</th>
<th>Cine 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity (%)</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Specificity (%)</td>
<td>96.5</td>
<td>98.8</td>
</tr>
<tr>
<td>Predictive value (%)</td>
<td>84.2</td>
<td>94.1</td>
</tr>
</tbody>
</table>

Digital, observation of digital arteriograms; Cine 2, second observation of cineangiographic film.

*In regard to first observation of cineangiographic film.

identifying lesions of 50% or greater, Cine 2 had a sensitivity of 90.6%, a specificity of 95.7%, and a predictive value of 90.6%. For identifying lesions of 70% or greater, Cine 2 had a sensitivity of 100%, a specificity of 98.8%, and a predictive value of 94.4%. Thus, in each case, Cine 2 was more predictive of significant disease (as defined by Cine 1) than Digital, and the differences in sensitivity and specificity between Digital and Cine 2 were more apparent for the subgroup of 50% or greater lesions than for the subgroup of 70% or greater lesions (Tables 2 and 3).

Results of Phantom Studies

With phantom coronary stenoses, the interobserver variability for Digital (2.5%) was similar to that for Cine (4.0%). Whereas both Digital and Cine slightly underestimated the actual percent diameter stenosis (mean difference, 3.9% for both techniques), there was no statistically significant difference between Digital, Cine, and the known percent diameter narrowing measurements by ANOVA. The results of linear regression analysis revealed a close correlation between actual values of diameter narrowing and those derived from either Digital or Cine (r=0.98 for both techniques).

Discussion

Although Digital has been proposed as an alternative to film-based imaging in the assessment of coronary artery disease,1 few data exist comparing Digital imaging with Cine. A previous study suggested that Digital and Cine methods yielded similar results in the assessment of stenotic lesions.13 Although that study used the same image intensifier and angles of view, the Digital and Cine images were obtained during separate contrast injections and with differences in radiographic technique. The data from the present study were derived from simultaneous, parallel images obtained under identical clinical and radiographic conditions.

Our results establish that, although the two imaging techniques are generally similar in the assessment of coronary artery disease, significant differences exist between Digital and Cine. Specifically, unprocessed Digital yields visual estimates of stenosis severity that are significantly greater than Cine, particularly with low-grade lesions and stenoses in small or branch vessels. Furthermore, Digital requires additional components in the imaging chain, most notably a video camera and television monitor for playback, each with its own inherent dynamic range and resolution limitations.

We designed this study to determine whether currently available Digital imaging can be used interchangeably with conventional Cine in the evaluation of coronary artery disease in clinical practice. In this regard, we recognized that image quality is complex and is determined by multiple interacting variables.14 Included among these variables are the radiographic system and the digital imaging device as well as patient-specific factors such as body size and cardiac anatomy. Although imaging of phantom vessels showed no difference between Digital and Cine methods, this result is not surprising. Phantom imaging avoids most of the variables that make quantification of human coronary lesions difficult. These variables include cardiac and respiratory motion, the irregular and eccentric nature of vessel lumens, vessel overlap and tortuosity, and the difficulty obtaining orthogonal views. Thus, technical specifications and phantom testing cannot predict the suitability of digital methods for clinical coronary arteriography; therefore, a clinical trial such as this is necessary. As the method of image analysis, we chose visual inspection of the arteriograms with manual calipers because this approach is used almost universally by practicing cardiologists for the diagnosis and quantification of coronary artery disease.

In this study, we applied several analyses to assess the comparability of Digital and Cine techniques for clinical coronary arteriography. Because one expects images of high technical quality to be interpreted similarly by multiple observers,15 we first examined interobserver variability in assessment of stenosis severity. We found that the overall interobserver variability of Digital and Cine was statistically equivalent. In addition, we identified two factors that influenced the amount of interobserver variability: vessel size and stenosis severity (Figure 3). Thus, if interobserver variability is used as the index of image quality, it would appear that Digital and Cine are essentially equivalent techniques.

It is difficult to directly compare our results with previous reports on interobserver variability because of differences in study design and statistical analysis.15–18 Early reports in the visual interpretation of coronary arteriograms showed somewhat greater interobserver variability than in our study.15–17 A very low interobserver variability was reported in a more recent study in which electronic calipers were used to measure preselected stenoses from single end-diastolic frames of cine film. In the present study, we did not preselect the stenosis, angle of view, or specific image frame for measurement of stenosis severity by the observers. Furthermore, magnification after acquisition was not used because optical enlargement is not a feature of most projector systems. We chose this study design to simulate the method of image analysis commonly used in clinical practice. As a consequence, not all lesions

Downloaded from http://circ.ahajournals.org/ by guest on November 6, 2017
were identified by every observer, and not all observers chose the same projection or frame for measurement, thus increasing the interobserver variability. In light of these methodological considerations, we believe the interobserver variability reported in the present study is consistent with previous work.

For Digital to serve as a substitute for Cine, it would be necessary for the two imaging modalities to yield comparable assessments of stenosis severity. However, we found that the overall stenosis grade by Digital was significantly greater than by Cine. As seen in Table 1, the pattern of overestimation by Digital was consistently identified in subgroups of lesions based upon vessel size, vessel branching order, and stenosis severity. In each of these subgroups, the comparison between Digital and Cine yielded lower slope and higher $y$ intercept values than did the comparison between Cine 1 and Cine 2. In addition, the Digital and Cine 1 comparisons yielded slightly lower correlation coefficients and slightly higher standard error values than did comparisons of Cine 1 and Cine 2 regardless of subgroup.

The likelihood of Digital overestimating Cine in individual patients was modified by vessel size, vessel branching order, and degree of narrowing. As illustrated in Figure 5, an overestimation by Digital of at least 15% diameter stenosis (the amount attributable to interobserver variability) occurred much more often with stenoses of less than 50% luminal diameter narrowing than with more severe lesions. In fact, the significant differences in stenosis severity between Digital and Cine fell below statistical significance when lesions less than 50% were excluded from analysis. Overestimation by Digital of at least 15% diameter stenosis was also more likely to occur with coronary vessels under 2 mm in diameter than with larger vessels and more likely for branch vessels than for first-order vessels.

Although, we report that Digital consistently overestimated Cine in the assessment of stenosis severity, it is important to realize that no standard of accuracy currently exists for the quantification of human coronary stenoses. The term ‘overestimation’ was chosen to describe the results of Digital in relation to Cine only because Cine is currently the clinical standard for diagnosis and therapeutic decision making. It must be recognized that previous studies that have compared the degree of coronary artery narrowing determined by Cine to the results of necropsy have consistently shown that Cine tends to underestimate the presence and severity of disease.19-22

We evaluated the potential clinical implications of the tendency for Digital overestimation of stenosis severity by calculating sensitivity, specificity, and predictive values for Digital in comparison with Cine. Digital was highly sensitive for the detection of what we considered clinically significant coronary disease. However, Digital identified more lesions than Cine, thus reducing the specificity and predictive values (Tables 2 and 3). In comparison, the second observation of Cine seldom led to significantly greater estimations of stenosis severity. Although we did not evaluate the clinical outcome of the patients in this study, their data suggest that therapeutic decisions may have been altered by reliance solely on Digital. Some caution is necessary when interpreting this statistic, however, because a second observation of Digital could not be performed with this study design.

The fact that Digital and Cine techniques are not identical in the identification and quantification of coronary artery disease should not be surprising. Digital imaging has been constrained in data transfer speed and storage capacity that has generally limited the image matrix to 512×512-pixels×8-bits gray scale at 30 frames/sec.

Currently used video cameras are inferior to Cine film in both dynamic range and spatial resolution. Images of reduced dynamic range may not accurately portray subtle shades of gray such as those at the borders of contrast-filled arteries. Because visualization of vessel borders is crucial to the determination of stenosis severity, it is possible for low dynamic range to augment the apparent severity of stenotic lesions. A related phenomenon, bloom, can obliterate crucial portions of an image such as contrast-filled coronary vasculature immediately adjacent to lung density, thereby creating false stenoses or accentuating true narrowings. The combined effects of reduced dynamic range and bloom on vessel borders may partially or even totally explain the overestimation of stenosis severity by Digital observed in this study.

Video cameras and film differ significantly in their representation of contrast and gray values. Video cameras generally exhibit a linear relation between exposure and brightness, whereas the Cine film exposure-density relation is always nonlinear, exhibiting an S-shaped transfer function known as the Hurter and Driffield curve. Furthermore, film-based imaging may lead to enhancement of the borders between black and white objects such as coronary arteries. This phenomenon, known as the edge and adjacency effect, is unique to silver-based film and is due to local differences in bromide ion concentration within the film during processing.

Video camera-based imaging also introduces electronic noise that is manifest as a granular background artifact that can degrade image quality. Video camera noise can be reduced by low-pass filtration, but filtration has the potential for removing a portion of the true image. Whereas excessive filtration can obscure spatial details, the resolution of the digital images used in this study was probably not impaired by the analog 5-mHz filter that was used before digitization of the video camera signal.

The requirement for analog-to-digital conversion is another major difference between Digital and Cine. Once recorded on film, a Cine image is preserved in its final form with a high degree of
spatial resolution. By comparison, the video image must be converted to digital pixels before storage. Although any given pixel may be partially white and partially black, it must be assigned a single value for the average gray level of the entire pixel. It is apparent that the number of individual pixels forming an image will determine the fidelity with which spatial details are digitally stored and that the number of individual gray levels will determine contrast. Because current limitations in data transfer speed and storage capacity generally permit a maximum 512×512-pixel×8-bit coronary imaging at 30 frames/sec, pixelation with this matrix imposes a definite limit on the spatial and contrast resolutions of the imaging system. Because at least two pixels are required to define the border of an object, the 512×512-pixel matrix (approximately 3.4 pixels/mm) has a theoretical spatial resolution of no more than 1.7 line pairs/mm. This is substantially less than the resolution of 4–4.5 line pairs/mm of modern image intensifiers.

The resolving power of any x-ray imaging system is further determined by a unique relation between the spacing of target objects and the resulting contrast between target and background of the recorded image. Whenever the contrast between the coronary vasculature and background is low, loss of detail may occur at spatial frequencies within the theoretical limits of resolution predicted from the pixel density alone. Thus, the fact that overestimation of stenosis severity of Digital occurred most frequently in small, distal vessels may be explained by either the marginal spatial resolution of the 512×512-pixel image matrix or by factors influencing contrast resolution (video camera dynamic range and eight-bit gray scale).

Although the spatial resolution of Digital is inferior to that of Cine, two factors tend to minimize the influence of this limitation on the quality of digital coronary arteriograms. First, the resolving power of the x-ray image intensifier system is limited by the quantum mottle that is present at x-ray doses that are clinically safe and technically feasible. Second, scatter and veiling glare, motion artifact, and focal spot blurring may degrade image quality for both Digital and Cine, further minimizing the differences between the two modalities.14,24,25

Because Cine and Digital images are displayed differently, the playback equipment must be considered in any comparison between the two imaging techniques. The television monitor used to display the Digital images has its own inherent limitations of dynamic range and resolution. In addition, the monitor has contrast and brightness controls that must be subjectively adjusted. Film projectors are a variable standard for comparison because gate-type projectors are optically superior to rotating prism projectors such as the one used in this investigation. Because the Digital and Cine images were viewed in different rooms, the difference in ambient lighting must be considered as another variable. Caliper measurements of lesion diameter from the television screen introduced some potential for parallax, a variable not present with measurement from the flat screen of the cine projector. All of these points of comparison emphasize the difficulty of isolating any single factor responsible for differences between Digital and Cine. Furthermore, the differences in this study may be specific to the imaging and playback equipment that was used. Although it is possible that different results may have been obtained by using different angiographic equipment, this study illustrates the need for caution when using any digital system as a substitute for cineangiography.

Digital imaging technology is improving rapidly. New generations of video cameras and new data storage and retrieval technologies are certain to improve spatial and contrast resolution. After image acquisition, digital subtraction techniques are capable of greatly enhancing contrast resolution, whereas filtration and edge enhancement algorithms have the potential to sharpen the borders of coronary arteries. By facilitating automated on-line quantitative arteriography, Digital may yield assessments of stenosis severity that are considerably more accurate and more reproducible than conventional Cine. This study used nonsubtracted, unprocessed digital angiographic images. Further study will be required to determine the effects of image processing and quantitative techniques on the assessment of coronary artery disease by Digital. Further research will also be required to determine which spatial frequencies constitute the clinically important portions of a digital coronary arteriogram and to determine the relative importance of spatial resolution, contrast resolution, and dynamic range. At this time, Digital and Cine would be considered complementary rather than interchangeable techniques, and the potential differences should be considered when making clinical decisions.

The multiple operational, image processing, and economic advantages of digital imaging would appear to make Digital the preferred modality for angiography in the future. In the process of conversion, physicians will relate the results of Digital to the existing standard of film-based angiography. The results of the present study demonstrate that, although generally similar, Digital assessments yield greater severity of stenosis than Cine. Although the present data do not provide information concerning the relative accuracy of each technique compared with an independent standard, it is clear that, at present, measures of percent luminal diameter reduction by Digital and Cine cannot be used interchangeably.

Acknowledgment
We gratefully acknowledge Betty Parks for the preparation of this manuscript.

References


**KEY WORDS** *cineangiography* *coronary arteriography* *digital angiography* *digital imaging*
Comparison of simultaneously performed digital and film-based angiography in assessment of coronary artery disease.
J C Gurley, S E Nissen, D C Booth, M Harrison, P Grayburn, J L Elion and A N DeMaria

Circulation. 1988;78:1411-1420
doi: 10.1161/01.CIR.78.6.1411

Circulation is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 1988 American Heart Association, Inc. All rights reserved.
Print ISSN: 0009-7322. Online ISSN: 1524-4539

The online version of this article, along with updated information and services, is located on the World Wide Web at:
http://circ.ahajournals.org/content/78/6/1411

Permissions: Requests for permissions to reproduce figures, tables, or portions of articles originally published in Circulation can be obtained via RightsLink, a service of the Copyright Clearance Center, not the Editorial Office. Once the online version of the published article for which permission is being requested is located, click Request Permissions in the middle column of the Web page under Services. Further information about this process is available in the Permissions and Rights Question and Answer document.

Reprints: Information about reprints can be found online at:
http://www.lww.com/reprints

Subscriptions: Information about subscribing to Circulation is online at:
http://circ.ahajournals.org//subscriptions/