Improving Detection of Coronary Morphological Features From Digital Angiograms

Effect of Stenosis-Stabilized Display

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Background We have developed a digital display method that stabilizes the motion of a stenosis in sequential frames of a coronary angiogram, allowing it to be scrutinized at high display frame rates. The purpose of this study was to determine whether this technique improves visual detection of low-contrast luminal morphological features.

Methods and Results An observer detection study was conducted using computer-simulated arterial segments containing known target features, inserted into digital coronary angiograms. Four observers performed a forced-choice detection of a simulated filling defect in each of 320 angiograms using the conventional and stenosis-stabilized dynamic displays (at 7.5, 15, and 32 frames per second) and a single-frame static display (total of 8960 detections). In a second simulated clinical task, three observers detected a bridging stenotic lumen in 600 angiograms using the two displays (3600 detections). In a third experiment, two angiographers rated the likelihood of intraluminal thrombus in 89 right coronary digital angiograms by consensus reading with both dynamic displays. Detectability of the simulated filling defect was similar for both dynamic display methods at 7.5 frames per second (averaging twice that for static images). As display rate was increased to 32 frames per second, detectability for the conventional display declined, whereas the stabilized display detectability increased for all observers (P<.05). On average, stabilization allowed detection of filling defects equivalent to a 71% increase in feature contrast. Response time for the conventional display averaged 12.9±4.7 seconds. For the stenosis-stabilized display, response time fell with increased frame rate (P<.05) to 4.9±1.2 seconds at 32 Hz, similar to the time for static images (4.6±0.8 seconds). The detectability of the bridging stenotic lumen was increased by 62% with the stabilization compared with conventional dynamic display (P<.00001). Consensus reading of coronary angiograms showed differences between the two dynamic display methods (κ=0.11) that may be explained by an improvement in observer uncertainty. A rating of definite for thrombus present or absent was more frequent with the stabilized display (39% versus 15%, P<.001).

Conclusions These data suggest that stabilized display of coronary angiograms significantly increases detectability, reduces the time required for detection, and improves observer uncertainty for the presence of small luminal morphological features. The method of angiographic display may thus have an impact on clinical coronary angiographic interpretation.

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Key Words • angiography • stenosis • imaging

Digital coronary cineangiography is now extensively used to improve image quality during diagnostic and therapeutic catheterization procedures. With the proliferation of percutaneous coronary interventional procedures, including balloon and laser angioplasty, atherectomy, and stenting, there has been increasing interest in detecting and characterizing intraluminal morphological features such as lesion eccentricity, thrombi, and intimal dissection. These features have been shown to correlate with outcome, and their detection may suggest alternative forms of treatment.1-6 Both digital and film-based coronary cineangiography have known limitations for the characterization of small intraluminal morphological features. Correlative direct visualization with angioscopy and intravascular ultrasound show that complex morphological features are frequently underestimated by angiography.7-11 Although morphological details may not be detectable in some cases because of inability to find a suitable projection free of vessel overlap and foreshortening, small morphological features frequently are obscured by image noise. In theory, the method of image display could improve the detection of coronary morphological features by enhancing the perception of the features relative to the noise. For example, quantitative perception studies have shown that more rapid display frame rates significantly improve the detection of simple stationary features against a background of simulated x-ray quantum mottle by increasing the observer-perceived amplitude of the feature relative to noise.12 With coronary images, however, a more rapid display frame rate increases the velocity of a moving coronary segment with respect to underlying patient structures. An observer must first visually track the motion of the stenosis before characterizing its morphological features. Although practical experience in the cardiac catheterization laboratory suggests that a moving vessel is easier to characterize when displayed in slow motion, the effect of display frame rate on coronary feature detection has yet to be quantified. Moreover, a display method that stabilizes the location of a stenosis in
sequential frames and thus minimizes visual tracking may take advantage of the observer’s ability to integrate noise in rapidly displayed image sequences. This type of display, which we will refer to as a stenosis-stabilized display, can be produced with image processing software on a digital angiography system or image display workstation. These considerations form the motivation for determining the effects of playback frame rate on detection of known morphological features in conventionally displayed and stenosis-stabilized digital coronary angiograms.

**Methods**

**Concept of the Stenosis-Stabilized Display**

A conventionally displayed digital cine angiogram is composed of a sequence of successive images played in the forward direction until the last image is displayed. The display then jumps back to the beginning of the sequence to form a repeating “loop.” Thus, a sequence four frames long would be displayed as 1, 2, 3, 4, 1, 2, 3, 4, and so on. Motion is displayed relative to the stationary x-ray source and imaging chain, as illustrated in the top row of Fig 1.

The stenosis-stabilized display is a method for displaying the cineangiogram so that (1) a specific coronary artery segment is kept stationary by “panning” the display and (2) discontinuous changes in the display between the end and beginning of the sequence are eliminated by a “palindromic” or forward and back display sequence. Stabilization of a coronary segment is achieved by digitally shifting, or “panning,” each image in the sequence so that a point on the coronary segment of interest remains in one position with respect to the observer, as illustrated in the bottom row of Fig 1. To create a palindromic display sequence, the image set is first played in the forward direction, seamlessly followed by the reverse direction back to the first image, then repeating. A four-frame sequence would thus be displayed 1, 2, 3, 4, 3, 2, 1, 2, 3, and so on. This eliminates the sudden change of scene at the end of the display loop due to cardiac, respiratory, or patient motion, as well as displacement caused by table panning or image gantry rotation. Although this palindromic sequence underemphasizes the first and last acquired images, this effect becomes relatively less important as the length of the image sequence increases.

**Digital Image Test Set**

A perceptual study was designed to evaluate the effects of image display methods for two simulated clinical tasks: detection of an intraluminal filling defect (experiment 1) and detection of a stenotic bridging lumen between two normal segments (experiment 2). Digital images were synthesized by combining a patient background noise image set with multiple computer-simulated coronary arteries and target features, i.e., “filling defect” or “bridging stenotic lumen.” The background noise image sequence consisted of a 32-frame digital clinical coronary angiogram acquired from a 99.5-kg patient in 30° right anterior oblique (RAO) projection at 30 frames per second with a 7-inch image intensifier field size (Advantx/DXC, General Electric Medical Systems). Imaging parameters included standard automatic exposure control at 0.30 μGy per frame and “extended dynamic range” video circuitry enabled. Digital images were obtained with a linear lookup table to achieve a 512x512-pixel matrix by 256-gray-level digital format. The spatial calibration factor was approximately 0.3 mm per pixel. All digital spatial filters were disabled. The images were transferred via Exabyte 8-mm digital tape to a network of Sun 4/370 and SPARC workstations capable of real-time image display rates (Sun Microsystems). Image generation was performed with the IDL software package version 2.2.2 (Research Systems Inc). Display of images and recording of responses for the observer performance studies were performed with a C program with a SunView user interface.

The background image sequence featured two primary sources of noise, quantum mottle and structure noise. Quantum mottle is image noise caused by the statistical variability in x-ray flux. This type of noise is characterized by randomness that is both spatially and temporally uncorrelated. Structure noise consists of patient structures in the area of the target that make target detection more difficult. These structures include the soft tissues of the cardiac silhouette, calcified but unopacified coronary arteries and aortic root, opacified filling and washout of a coronary vessel, ribs, spine, lung markings, stainless steel surgical vascular clips, and poststernotomy retention wires. Patient background structure noise is both spatially and temporally correlated but differs from one frame to the next because of normal cardiac and respiratory motion.

Four mathematically simulated straight “coronary segments” were generated by projecting three-dimensional vertically oriented right cylinders, 3.0 mm (10 pixels) in diameter by 20 mm (67 pixels) in length, into a 256-pixel-wide by 128-pixel-tall array. The target features were similarly projected. In experiment 1, a “filling defect” consisting of a hemisphere 1.5 mm in diameter (5 pixels) was placed randomly at the center of one of the four coronary segments. In experiment 2, a “bridging lumen” consisting of a right cylinder 0.6 mm in diameter (2 pixels) was randomly positioned between either the left or right pair of “coronary segments” and oriented 45° from vertical. The intensity or brightness of each pixel was calculated to create simulations with density cross-sections observed in real coronary arteries filled with x-ray-absorbing contrast material and imaged by standard cineangiographic techniques. The details of this simulation are described in “Appendix A.” To simulate typical slightly erratic, phasic coronary motion, the location of the cylinders was varied from frame to frame along the horizontal axis according to a random-walk procedure (“Appendix A”). This algorithm was judged to result in realistic-appearing cardiac motion with approximately one “cardiac cycle” over the 32-frame image sequence. The simulated arteries and target features were combined with 256x128 subarrays selected from random locations within the 512x512 background image sequence, thus creating an unlimited number of unique trial sequences with a large spectrum of quantum and structure noise in the region surrounding the feature to be detected. Fig 2 shows frames containing the simulated vessels and target features.

In both perception experiments, image sequences were displayed as conventional cine loops in which the four simulated arteries appeared to translate with respect to a relatively stationary background. At the end of the image sequence, the display looped back to the first image and then redisplayed the sequence, resulting in a visible “jump” of the artery/target and background. Each image set was also processed to be a stenosis-stabilized sequence, created by digitally shifting the entire image on the display in the opposite direction to the translation of the artery. With this display, the four simulated vessels appeared stationary or “stabilized,” whereas the background underwent phasic motion. These images were shown in the palindromic sequence already described. Thus, all image sequences were displayed as a conventional cine loop and as a stenosis-stabilized palindromic loop. Additionally, in experiment 1, the first image in each set was displayed as a single static image.

The images were displayed unzoomed, occupying a 256x128-pixel matrix in the center of a 19-inch, 1100x900-pixel high-quality black and white monitor (Tektronix GMA 201) with a linear gray scale, gamma 2.2, and midrange gray level of 28 candela per square meter. Ambient lighting was constant throughout the study.
Observer Performance: Simulation Experiment 1

The purpose of this study was to determine the detectability of simulated filling defects in static images and in dynamic image sequences displayed as conventional cine loops and as stenosis-stabilized images. Before participating in the study, each of four observers was trained by practicing on image sets in which the contrast, C, of the target was adjusted to achieve an accuracy of between 50% and 95% for all three types of display, since the coefficient of variation of the detectability index (see Equation 2 in "Appendix A") for a given number of trials is larger outside this range. 13 Values of C used were 0.5, 0.5, 0.6, and 0.9 for observers 1 through 4, respectively. Once chosen, this observer-specific contrast was fixed. The range of contrast for the filling defect was within the range encountered clinically for features of similar size.

The trained observers then participated in test viewing sessions spread over 3 to 6 weeks. A session consisted of reading one set of 80 different image sequences of a single display mode (static, conventional loop, or stenosis-stabilized display) at one display frame rate. The conventionally displayed and stenosis-stabilized images were shown on the video monitor at 7.5, 15, and 32 frames per second. (Because the video monitor was able to switch from one frame to the next between screen refresh scans, there was no perception of flicker at any frame rate, unlike slow motion on some cinefilm projectors.) Viewing was performed under each display condition on four separate occasions, for a total of 320 observations per condition. Each session typically required about 30 minutes. Altogether, each observer participated in 28 reading sessions for a total of 8960 target detection trials for the four observers.

Observers were instructed to select which of the four segments they believed was most likely to contain the target (four-alternative forced-choice, or "4-AFC," design). They were allowed to place themselves at a comfortable viewing distance and to perform normal eye and head movements. Each target detection trial was initiated by pressing a key to start the display sequence. Subjects had unlimited time to reach a decision. When the target was detected, a second keystroke halted the sequence and displayed the last image. The artery segment containing the target was selected by clicking on it with a mouse. The subject was provided with audible feedback if the correct segment was selected. The display program automatically recorded the observer's responses and the time between the first and second keystrokes.

Observer Performance: Simulation Experiment 2

Using the results from experiment 1 as a guide to determine the optimal display frame rate for each display type, three trained observers detected the presence of a "bridging stenotic lumen" between the left or right pair of simulated vessels (2-AFC design). The signal contrast C was 1.0 for the three observers. For each reading session, 100 different image sequences similar to those used in experiment 1 were viewed under two display conditions: conventional cine loops at 15 frames per second or as stabilized image sequences at 32 frames per second. As an additional constraint, observers were given a time limit of 4 seconds for each trial. Each observer analyzed 600 sequences per condition. Thus, there were a total of 3600 feature detection experiments for the three observers.

Observer Performance: Clinical Images

To investigate the potential appropriateness of the stabilized display for clinical image interpretation, a preliminary study was performed to evaluate observer performance for the detection of intraluminal thrombus in a sample of real coronary angiograms. Eighty-nine 35-mm cinefilm right coronary angiograms (47 RAO and 42 left anterior oblique) were selected to represent a wide range of stenosis severities with a high frequency of complex morphological features, including lumen edge irregularities, plaque ulcerations, and intraluminal filling defects. Image quality ranged from sequences with low contrast and high noise to excellent-quality images. The images were acquired with biplane digital cineangiography systems (Advantx/DXC, General Electric Medical Systems) using
a 7-inch field size and standard 30-frame per second simultaneous digital and cinefilm acquisition protocols. The corresponding, unenhanced, 512x512 by 8-bit digital image sequences composed of 30 consecutive opacified frames were transferred from tape storage to the Sun display workstations. The sequences were processed as edge-enhanced images to match the real-time spatial filtering displayed in the catheterization laboratory. A 256x256 subarray of the original images was displayed on the same monitor as in experiments 1 and 2. Stenosis stabilization was accomplished by placing a cursor with a mouse over the center of the stenosis in each frame and automatically shifting that location to the center of the display. Fig 1 shows an example of conventional and stabilized sequences from this study.

Two experienced angiographers viewed the image sequences together in four divided sessions. Each reading session included approximately one half of the image sequences displayed either as conventional cine loops at 15 frames per second or as stenosis-stabilized sequences at 32 frames per second. The angiographers were asked to rate the presence of intraluminal “thrombus” on a five-point scale that specified that the feature was (1) definitely absent, (2) probably absent, (3) indeterminate, (4) probably present, and (5) definitely present. The morphological definition used to determine the presence of a thrombus was an intraluminal nonopacified mass that was globular or irregular in appearance. The consensus rating of the angiographers was recorded into an automated database.

**Data Analysis**

Detectability for each condition (combination of display mode and frame rate) was expressed as \( d' \), a measure of...
performance based on the equal-variance gaussian model of signal detection theory (see "Appendix B"), which may be calculated from the number of alternative forced choices and the proportion of correct detections.\textsuperscript{14} We chose d' as the primary parameter of observer performance because, unlike a parameter of accuracy such as percent correct, d' has been shown to be linear with the contrast of the signal for both static and dynamically displayed images.\textsuperscript{12,15} To compare the relative effects of display format and frame rate between observers, d' was normalized relative to each observer's performance in the conventional cine loop display at 7.5 Hz, such that

\begin{equation}
    d'_\text{Normalized} = \frac{d'}{d'_c, 7.5 \text{ Hz}}
\end{equation}

Thus, a \(d'_\text{Normalized} \) of 2.0 can be interpreted as equivalent to a doubling of the feature contrast in the conventional display.

ANOVA for repeated measures was performed to test for the presence of session-to-session variability (for example, due to observer learning). Comparison of detectability between display formats was made for each observer using the \( z \) statistic at the 95\% significance level (\( P<.05 \)). Comparison of the average response times for the six display conditions was performed by unpaired \( t \) test, using the mean and SD of four repeated sessions for each condition. The significance levels for all statistical tests were adjusted to account for the six paired comparisons for each observer (Bonferroni correction).\textsuperscript{16} In the clinical study, observer agreement between display types was quantified by the \( \kappa \) statistic, for which a value of 0 indicates chance agreement and a value of 1.0 denotes perfect agreement. Significant differences for the angiographic consensus readings were evaluated by \( \chi^2 \) analysis. Values in text and figures are the mean \pm SD unless otherwise specified.

## Results

### Detection of Simulated Features

#### Experiment 1

Fig 3 shows the detectability index d' for the task of detecting simulated luminal filling defects by the individual subjects as a function of display mode and frame rate. Fig 4 shows the normalized detectability for all four observers combined. For the conventional display at the slowest dynamic display rate (7.5 frames per second), there was a highly significant improvement in target detectability compared with static images (\( P<.01 \)), with an average relative value of 2.0\pm0.7. Detectability was similar at 7.5 and 15 frames per second but deteriorated significantly (\( P<.05 \)) at the highest display rate of 32 frames per second. At the slowest display rate, detectability for the stenosis-stabilized display and the conventional cine loop display did not differ for any observer. Stenosis stabilization was associated with a monotonic improvement in target detectability with increasing display frame rate for each of the four observers. At the highest display rate of 32 frames per second, detectability ranged from 1.2 to 2.3 times the best performance achieved with the conventional display (\( P<.05 \)). Although individual observer values of d' differed, the dependence of detectability on frame rate was similar. Average performance of the four observers was 71\% higher for the stenosis-stabilized display than for the best conventional display and 311\% higher than for static images.

Fig 5 summarizes the effects of display mode and frame rate on the average time required for "filling defect" target detection. Static images were associated with the shortest decision time, averaging 4.6\pm0.8 seconds. Conventional cine loop sequences had longer detection times, averaging 12.9\pm4.7 seconds, 2.8 times longer than for static images, but not related to display frame rate. Stenosis-stabilized sequences had a significant trend for reduced decision times with increasing frame rate. At the highest frame rate, decision time averaged 4.9\pm1.2 seconds, which was not significantly different from the static image display. These data show that the stenosis-stabilized format displayed at the fastest rate allowed observers to perform the detection task at the highest rate as well as with the highest accuracy.

#### Experiment 2

Fig 6 shows the effect of display conditions on the detection of the simulated bridging stenotic lumen for the three individual and combined observers. The performance of each observer was significantly improved with the stabilized display viewed at 32 Hz compared with the conventional cine loop displayed at 15 Hz.
(P<.002). On average, the detectability index, d', improved by 62% with the stabilized display (P<.0001).

Feature Detection in Clinical Images

The Table compares the consensus ratings of the two angiographers for the presence of thrombus by display type. There was little more than chance agreement between the two display methods with κ=0.11. The discrepancy between the methods may be explained by the distribution of ratings with regard to observer uncertainty. An indeterminate rating was much less frequent with the stabilized display (2 [2%] versus 28 [31%]; χ²=27.1, P<.0001). Likewise, a rating of thrombus definitely present or absent was more frequent with the stabilized display (35 [39%] versus 13 [15%]; χ²=15.3, P=.0001).

Discussion

The first part of the study, which realistically simulated the signal and noise conditions during clinical digital coronary angiography, confirmed the common observation that detectability of small low-contrast intraluminal features is enhanced in dynamic displays compared with static images. Interestingly, feature detectability in conventional cine loop displays was better at slow-motion display rates of 7.5 and 15 frames per second and deteriorated significantly as the display rate increased to 32 frames per second. In comparison with a single frame, detection of simulated filling defects in the conventional dynamic display took 2.8 times longer, even when there were only four possible locations for a target lesion.

A new dynamic display method, known as stenosis stabilization, was tested in comparison with conventional displays in the same simulations and in clinical coronary angiographic sequences. Detection accuracy for the simulated filling defect was the same as the conventional cine loop when displayed at 7.5 frames per second but significantly and monotonically improved as the display rate increased to 32 frames per second, when observers detected features 2.6 times faster than with the conventional cine loop display. The magnitude of improvement in detection frequency was equivalent to a 71% increase in feature contrast compared with the conventional cine loop display and a 311% increase compared with static images. Similarly, in a perception study that simulated a second clinical task, the detection of a bridging stenotic lumen, performance improved, with the stabilized display equivalent at...
Consensus Thrombus Rating in Clinical Angiograms

<table>
<thead>
<tr>
<th>Thrombus Rating, Stenosis-Stabilized Display</th>
<th>Conventional Cine Loop Display</th>
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<tbody>
<tr>
<td></td>
<td>Absent</td>
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<tr>
<td>Absent</td>
<td>3</td>
</tr>
<tr>
<td>Probably absent</td>
<td>3</td>
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<tr>
<td>Indeterminate</td>
<td>0</td>
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<tr>
<td>Probably present</td>
<td>1</td>
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<tr>
<td>Present</td>
<td>0</td>
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<td>Sum</td>
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$k=0.11$.

to a 62% increase in contrast compared with the conventional cine loop display.

In a preliminary experiment with clinical coronary angiograms, the feasibility of applying the stabilized display was evaluated for the task of rating the likelihood of the presence of features consistent with intraluminal thrombus. Stenosis stabilization significantly reduced observer uncertainty for the presence or absence of intraluminal filling defects compared with the conventional cine loop digital display. Taken together, these results suggest that reducing the relative motion of the vascular segment of interest may be useful for improving detection and reducing uncertainty for coronary morphological features.

Feature Detection in Dynamic Displays

A successful theoretical model for visual target detection has been described for static medical images.\textsuperscript{17-20} Target detection in static and dynamic images, however, involves different perceptual mechanisms. Visual spatial integration is required to detect the target in both displays, whereas the improvement of detection accuracy in dynamic displays requires temporal integration. Dynamic display reduces the effect of uncorrelated noise because the observer is able to integrate the feature and the noise from multiple frames to increase the effective signal-to-noise ratio. We have previously shown that detection of a stationary target against a background of dynamic random noise can be modeled by the temporal integration of a number of frames proportional to the display frame rate, with a visual integration time "window" of 800 to 1500 milliseconds.\textsuperscript{12}

We hypothesize that extracting morphological features from coronary angiograms involves additional visual perceptual mechanisms. The first requirement is to visually track the motion of a segment of interest either by smooth pursuit or multiple saccadic eye movements. Tachycardia, increased contractility, and projection orthogonal to the major vector of displacement can make coronary motion too fast to comfortably track. For example, angiographers are familiar with the difficulty of evaluating the right coronary artery in an RAO projection when coronary motion is exaggerated. Additionally, jumping back to the first image at the end of a sequence can produce a very large displacement occurring in a single frame time, resulting in momentary visual mistracking of the vessel.

Once the stenosis is visually tracked, the observer must distinguish low-contrast morphological features from the background clutter composed of two different types of noise: (1) quantum mottle, caused by random spatial and temporal variability in x-ray flux, and (2) overlying nondiagnostic patient structures, including bones and soft tissues, which are spatially ordered and correlated from one frame to the next. Temporal integration will reduce the apparent quantum noise relative to the target signal but will not affect the contribution of structure noise unless structures are in motion with respect to the retina. The effect of structure noise may be reduced by visual cues, leading to the recognition of underlying structures, and thus structure noise can be "overread" by the observer.

The results of this study can be understood in terms of these visual perception mechanisms. In the conventional cine loop display, smooth-pursuit visual tracking errors may be greater at higher frame rates. Saccadic eye movements are required to track high-velocity motion, and such eye movements temporarily interrupt vision. These errors and saccades may enhance the noise or interfere with the temporal integration of successive images, thus decreasing feature detection accuracy at higher display frame rates. With the stenosis-stabilized display, visual tracking errors are minimized and saccadic eye movements are eliminated, permitting uninterrupted temporal integration. The untracked motion of nondiagnostic patient structures may be helpful in reducing this source of noise by the mechanism of temporal integration and by the motion, providing an additional cue to the observer that the structure is indeed noise and should be overread. Detectability increased monotonically with display rate, consistent with the integration of more sequential frames and a reduction in the effects of both patient structure noise and quantum noise.

The considerable variation between observers for detecting low-contrast features suggests that they differ in their ability to perform temporal integration. In experiment 1, the contrast of the feature target was adjusted for each observer, yet there were still large performance differences between observers. The de-
tectability achieved in the conventional cine loop display by observer 3, who was the least experienced with coronary angiograms, was not significantly greater than for static display. Although the target feature contrast, C, of observer 3 was 69% higher than that of the other observers, the absolute detectability index for conventional cine loop display was reduced by 41%. The best performance for the conventional display was achieved by observer 4, an experienced angiographer who regularly uses this type of display to make intraprocedural decisions during angioplasty. The performance of observers 1 and 2 was intermediate between the most experienced and least experienced observers. Observer 1 has 10 years’ experience viewing coronary angiograms, and observer 2 is an experienced visual perception subject, but they are not angiographers. These findings suggest that observer experience with a particular perceptual task and display type may be an important factor that modulates performance. Although there were quantitative differences between observers, importantly, the dependence of detectability on frame rate was consistent among observers for a given display type.

Study Limitations

One potential limitation of this study is the predominant use of computer simulations rather than real morphological features. Another limitation is that the results may be affected as a function of the specific feature detection task and motion of the simulated arteries. We did not assess the impact of changing or complex geometric features, and motion was not varied in this study. An important strength of our method, however, is that the simulated structures have exactly known features (shape, dimension, location, contrast, and motion) that can be precisely duplicated in a variety of background structure, quantum mottle, and display conditions. This allows quantification of the effects of varying features, noise, and display methods on observer performance, which is a necessary first step in optimizing that performance in actual coronary angiograms. In addition, there may be some value in the use of simulated known angiographic features for training angiographers to classify coronary artery lesion morphology more accurately.21

The subjective impression of the angiographers was that the stenosis stabilization display was particularly helpful when coronary motion was exaggerated and when image noise obscured features in the conventionally displayed cine loops. Although we have presented preliminary information that improved detection in simulations is associated with more observer certainty for the presence or absence of actual morphological features, it is too early to conclude that stenosis stabilization will enhance the subjective analysis of clinical coronary angiography. The experiment with clinical image sequences was limited to the right coronary artery, detection of a single angiographic feature, and there was no comparison with the underlying pathoanatomy. Moreover, intraobserver and interobserver variabilities have yet to be established. Verification of the utility of this method for clinical diagnosis will require an extensive series of clinical angiograms containing a variety of morphological features independently validated by other techniques such as intravascular ultrasound or angioscopy.

Stenosis stabilization will not be helpful in every case. The problems of vessel overlap and foreshortening remain. Detection will not be enhanced when vessel motion relative to background structures is minimal. Rapidly moving vessels will still be blurred because of the finite requirements of the x-ray tube pulse width. Rapidly moving structure noise can be subjectively distracting, especially when the structures exit the image borders and suddenly return. This last effect, however, had little influence on results of the simulation studies, in which detection accuracy continued to improve with increasing display frame rate.

Observer detection of morphological features is inherently subjective. Validated and reliable automatic feature-detection algorithms may be less subjective but are currently not available as they are for quantitative measurement of coronary dimensions. Moreover, objective feature detection and quantitative coronary measurements will be less influenced by noise if multiple frames are averaged. We are now using a prototype feature-detection algorithm to automatically track a stenosis from frame to frame. With this approach, stenosis stabilization may serve as a first step to automatically perform multiframe objective analysis of coronary dimensions and characterization of morphological features.

Finally, even if this type of stabilized display improves detection of angiographic features, it does not provide further insight into their pathogenesis, which may be critical for guiding therapy. Nevertheless, the present data suggest that stenosis stabilization may be a practical and effective method for improving detectability of low-contrast coronary features frequently not well visualized by angiography and may thus improve clinical image interpretation for diagnostic coronary angiography and coronary angioplasty.

Appendix A

Simulated Feature Generation

The simulated coronary segments were generated by empirically setting the linear attenuation coefficient of contrast material, $\mu$, to 0.10/mm to produce cylinders with the same projected intensity as real angiograms of coronary arteries with the same diameter. Imaging system blur caused by the physical extent of the x-ray focal spot and image intensifier unsharpness were simulated by convolving the projected cylinders with a spatially symmetric gaussian point spread function of SD 0.30 mm.

Filling defects were similarly created by calculating the projection of a 1.5-mm- (5-pixel-) diameter hemisphere. After the target was blurred in the same manner as described for the cylinders, the target was subtracted from the center of one of the four simulated arterial segments, randomly chosen for each trial. The simulated arteries and targets were combined with each frame of the clinical digital coronary angiogram by exponential attenuation, analogous to the x-ray absorption process, so that pixel brightness or intensity, I, was determined by

$$I = I_o e^{-\mu(P_t - P_C)}$$

where $I_o$ is the original pixel intensity, $P_t$ and $P_C$ are the projected thicknesses of the cylinder and target, respectively, $\mu$ is the attenuation coefficient, and C is a multiplicative “contrast” factor used to produce targets of different visual contrast but the same size.
Simulated Coronary Motion

In a preliminary study, we analyzed a "worst case" of exaggerated coronary motion by tracking the displacement of the midportion of the right coronary artery in 13 consecutive diagnostic angiograms obtained in the 30° RAO projection. The sequences contained no panning and were acquired with a 7-inch image intensifier field size with a matrix size of 512×512. The long axis of displacement averaged 121±27 pixels and was nearly horizontal to the pixel matrix. The short axis of motion was significantly smaller at 22±8 pixels (P<.001). To simulate less extreme coronary motion, we varied the location of the simulated coronary vessels in the horizontal direction according to a random-walk procedure so that the distance, Jn, moved from frame (n-1) to frame (n), was determined by

\[
J_n = \pm \left| J_{n-1} + aR \right|
\]

(3)

where the sign determines the direction of motion, the "acceleration," a, was empirically set to 5.07, and R is a uniformly distributed pseudorandom number in the range ±1.0. The motion was allowed to range over 64 pixels, which was 25% of the displayed image. Each time the vessel reached the left extreme, the value for \(J_{n-1}\) in Equation 3 was arbitrarily set to 2.7 pixels and the sign was set to +1, producing motion to the right. At the right extreme, \(J_{n-1}\) was set to −0.4 and the sign was set to −1, producing slower motion to the left.

Appendix B

The index of detectability used in this article is known in signal detection theory as \(d'\). Detection of the simulated "target" is assumed to depend on the magnitude of the internal response of the observer to the stimulus image at each possible location of the target. The nature of this internal response is not necessarily known, although it is assumed to be a random variable with a gaussian distribution whose mean values for signal and background areas are different. The variance of the gaussian distribution reflects the existence of noise in the image as well as random fluctuations in the observer's internal response to a given stimulus. In a multiple-alternative forced-choice task, the observer is assumed to choose the alternative corresponding to the highest internal response. If there is no overlap between the two distributions, this strategy will result in 100% correct detections. At the other extreme, when there is no difference between the means, the target is undetectable, resulting in a simple chance rate of correct detections—25% in the case of our four-alternative task. Between these extremes, the rate of correct detections is determined by the degree of overlap of the two distributions, which is conveniently quantified by the separation of the means in units of their SD, \(\sigma\). This degree of overlap is the definition of \(d'\), i.e.,

\[
d' = \frac{\mu_s - \mu_b}{\sigma}
\]

(4)

where \(\mu_s\) and \(\mu_b\) are the mean internal response values for signal and background areas, respectively.

A natural consequence of this definition is that, unlike percentage correct, \(d'\) is linear with the physical contrast of the target signal (provided that the observer's internal response is). This has been demonstrated for static and dynamic displays. Thus, \(d'\) was selected as the main parameter of this study because it relates performance to the physical signal.

For a forced-choice experiment with \(M\) alternatives (i.e., M-AFC), the percent correct detections, \(P_c\), is related to \(d'\) by

\[
P_c(M,d') = \int_{-\infty}^\infty \Phi(M-1)(x) \Phi(x-d') dx
\]

(5)

where

\[
\Phi(x) = \frac{1}{(2\pi\sigma^2)^{1/2}} \exp\left(-\frac{x^2}{2\sigma^2}\right)
\]

is the probability that the signal distribution takes a value \(x\), and

\[
\phi(x) = \int_{-\infty}^x \frac{1}{(2\pi\sigma^2)^{1/2}} \exp\left(-\frac{y^2}{2\sigma^2}\right) dy
\]

is the probability that the noise distribution takes a value less than \(x\).

Statistical variance of \(d'\) was estimated by propagating the variance of \(P_c\), for each observer and display condition using equation 5, where the variance of \(P_c\) for \(n\) trials based on the binomial distribution is given by

\[
\sigma_{P_c}^2 = \frac{P_c(1-P_c)}{n}
\]

(8)

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