Objective Evaluation of Regional Left Ventricular Wall Motion During Dobutamine Stress Echocardiographic Studies Using Segmental Analysis of Color Kinesis Images

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OBJECTIVES
To test the feasibility of objective and automated evaluation of echocardiographic stress tests, we studied the ability of segmental analysis of color kinesis (CK) images to detect dobutamine-induced wall motion abnormalities and compared this technique with inexperienced reviewers of conventional gray-scale images.

BACKGROUND
Conventional interpretation of stress echocardiographic studies is subjective and experience dependent.

METHODS
CK images were obtained in 89 of 104 consecutive patients undergoing clinical dobutamine stress studies and were analyzed using custom software to calculate regional fractional area change in 22 segments in four standard views. Each patient’s data obtained at rest was used as a control for automated detection of dobutamine-induced wall motion abnormalities. Independently, studies were reviewed without CK overlays by two inexperienced readers who classified each segment’s response to dobutamine. A consensus reading of two experienced reviewers was used as the gold standard for comparisons. In a subgroup of 16 patients, these consensus readings and CK detection of wall motion abnormalities were compared with coronary angiography.

RESULTS
The consensus reading detected ischemic response to dobutamine in 43 of 1958 segments in 23 of 89 patients. Automated detection of stress-induced wall motion abnormalities correlated more closely with the standard technique than the inexperienced reviewers (sensitivity 0.76 vs. 0.55, specificity 0.98 vs. 0.94 and accuracy 0.97 vs. 0.92). When compared with coronary angiography in a subgroup of patients, analysis of CK images differentiated between normal and abnormal wall motion more accurately than expert readers of gray-scale images (accuracy of 0.93 vs. 0.82).

CONCLUSIONS
Analysis of CK images allows fast, objective and automated evaluation of regional wall motion, sensitive enough for clinical dobutamine stress data and more accurate than inexperienced readers. This method may result in a valuable adjunct to conventional visual interpretation of dobutamine stress echocardiography. (J Am Coll Cardiol 1999;34:409–19)

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From the time that Tennant and Wiggers (1) first described the immediate mechanical manifestations of myocardial ischemia, which were subsequently verified by abundant clinical and experimental data, different imaging techniques have focused on the evaluation of regional left ventricular (LV) wall motion. Echocardiography is currently the leading real-time imaging modality used to assess regional wall motion abnormalities. When performed immediately after exercise or during pharmacologic stress, echocardiography is sensitive enough to detect regional wall motion abnormalities before the onset of electrocardiographic changes associated with ischemia (2,3). Accordingly, this methodology has become a cost-effective alternative to myocardial scintigraphy (4) and is widely used for the diagnosis of coronary artery disease (CAD).

However, conventional echocardiographic assessment of LV wall motion is based on visual interpretation of dynamic gray-scale images, which is qualitative, subjective and expe-
Objective Interpretation of Stress Echocardiography

Abbreviations and Acronyms

CAD = coronary artery disease
LV = left ventricular

Experience dependent. The interpretation of images obtained during stress testing is even more subjective than that of resting images (5), since it is based on visualizing changes in endocardial excursion and myocardial thickening assessed at different levels of stress, which are usually confounded by concomitant changes in heart rate and increased cardiac translation. Previous attempts to develop more objective approaches to evaluate regional wall motion have been based primarily on time-consuming, multi-frame manual tracing of the endocardial boundaries (6–12), and therefore, remain impractical for routine clinical use. We have previously described a new quantitative technique based on segmental analysis of color kinesis images, which reflects the magnitude and timing of LV endocardial motion (13,14). This technique allows objective evaluation of regional systolic and diastolic LV function at rest (13–15), and was shown to correlate closely with expert readings of conventional grayscale echocardiograms (14). Our previous results also demonstrated the feasibility of using segmental analysis of color kinesis images to objectively assess stress-induced wall motion abnormalities (13).

The aim of this study was to determine the applicability of this technique in consecutive patients referred for dobutamine stress echocardiography. To determine the clinical value of this technique, we compared its ability to detect dobutamine-induced wall motion abnormalities with that of inexperienced reviewers of conventional stress echocardiographic images using a consensus of experienced reviewers as the “gold standard” for comparisons. In addition, in a subgroup of patients with positive stress tests who underwent subsequent coronary angiography, our findings obtained with color kinesis, as well as consensus expert readings, were compared with coronary angiography.

METHODS

Study population. One hundred four consecutive patients undergoing dobutamine stress echocardiography were screened for this study. Fifteen patients were excluded for the following reasons: four patients had left bundle-branch block, and 11 patients had image quality that allowed visualization of <75% of the endocardial boundary. The remaining 89 patients (81%) were enrolled in the study.

Stress protocol and image acquisition. After blood pressure reading and 12-lead electrocardiogram were obtained, baseline echocardiographic images were acquired with the subject in the left lateral decubitus position. Intravenous dobutamine infusion was initiated at 5 μg/kg/min, which was then progressively increased to 10, 20, 30 and 40 μg/kg/min. At each dose, blood pressure and electrocardiogram were monitored. If target heart rate was not reached with the highest dose of dobutamine, atropine (0.2 to 1.0 mg i.v.) was administered.

Ultrasound imaging was initially performed at baseline in the parasternal short and long axis as well as apical four- and two-chamber views using a 2.5- or 3.5-MHz transducer (SONOS 2500; Hewlett-Packard). After optimizing image quality and gain settings for endocardial tracking by acoustic quantification (16), color kinesis was activated to color encode systolic endocardial motion throughout the entire protocol within a predefined region of interest surrounding the LV cavity (13,14). To facilitate quick transitions between imaging planes, image settings and regions of interest were digitally saved for each particular view at baseline and were retrieved to allow repeated imaging of the same view during subsequent phases of the protocol with the same settings.

Then, imaging was repeated at low dose (10 μg/kg), peak dose (40 μg/kg) and again during the recovery period, once blood pressure and heart rate returned to their baseline values (typically 10 to 20 min after infusion is terminated). In each view, images were acquired during end-expiration using the commercial software package for stress echocardiography, which acquires one beat per protocol phase in each view. Images obtained during all phases of the protocol were stored on optical disk for off-line review and separate computer analysis of the color kinesis overlays.

To test the reproducibility of our methodology, instead of saving color kinesis images during the recovery period, an additional set of short axis and apical four-chamber images was acquired from nine patients under peak dobutamine infusion and saved on optical disk.

Conventional interpretation of wall motion. Digitally saved images were reviewed without color kinesis overlays jointly by two experienced reviewers (mean of five years of experience, >2,000 dobutamine stress tests), whose consensus interpretations of LV regional wall motion were subsequently used as a “gold standard” for comparisons. These interpretations included segment-by-segment grading of regional wall motion as either normal or abnormal (including hypokinetic, akinetic or dyskinetic) at each phase of the protocol using the official guidelines for the segmentation of standard views (17). Independently, the same images were reviewed and graded segment-by-segment by two relatively inexperienced readers of dobutamine stress tests, second-year cardiology fellows who completed six months of training in echocardiography, including <100 dobutamine studies (American Society of Echocardiography level II of training).

Analysis of color kinesis overlays. Digital images obtained at rest and at peak dobutamine infusion were reviewed off-line on a personal computer, and end-systolic color kinesis overlays were analyzed using a previously described custom-designed software (13). Briefly, images in
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To allow automated detection of dobutamine-induced regional wall motion abnormalities, data obtained in each patient at rest was used as the reference for comparison. Dobutamine-induced wall motion abnormalities were automatically detected in individual segments when reduction in regional fractional area change of more than 40% of the baseline value was noted. This threshold was set on the basis of the results of a previous study (14), where we observed normal variability of up to 20% in data obtained at rest, and the results of the reproducibility protocol, which showed that dobutamine induced increase in heart rate and cardiac translation could double the normal variability (13).

Detection of ischemic response in individual patients.

To determine the clinical value of this technique, we defined a patient showing ischemic response to dobutamine as at least two contiguous segments in the same view or two overlapping segments in different views changing classification from normal at rest to abnormal at peak dobutamine. On the basis of this definition, we calculated the agreement and disagreement between each, the conventional interpretation by inexperienced observers and the automated technique, with the standard readings on a patient-by-patient basis. In other words, we calculated how many patients had ischemic response according to the consensus expert interpretation, how many of them were missed by each, the inexperienced readers and the objective technique and how many others were falsely identified as having ischemic response by each technique.

Comparisons with coronary angiography.

Color kinesis data obtained in a subgroup of patients with positive stress tests who subsequently underwent coronary angiography were compared on a segment-by-segment basis with the findings of coronary angiography as follows. In each patient, each of the 22 segments in the four standard echocardiographic views was classified as either normally perfused or potentially underperfused based on the location and severity of coronary stenosis, which was defined as significant for >70% luminal narrowing. For each segment, this classification was compared with the results of the automated detection of dobutamine-induced wall motion abnormalities based on segmental analysis of color kinesis images.

Statistical analysis.

Conventional interpretations of regional LV wall motion made by each inexperienced reviewer at rest and during peak dobutamine infusion were compared on a segment-by-segment basis with the corresponding gold standard consensus reading of the experienced reviewers. Regional ischemic response was defined as a transition of a segment from being classified as normal at rest to abnormal at peak dobutamine infusion. The numbers of concordant readings (true positive and true negative) and discordant readings (false positive and false negative) were used to calculate the sensitivity, specificity, overall accuracy and positive and negative predictive values of the conventional reading by inexperienced readers.

The performance of the algorithm for objective detection of stress-induced wall motion abnormalities based on the analysis of color kinesis images was also compared with the same gold standard. The numbers of concordant and discordant readings were used to calculate the sensitivity,
specificity, accuracy and positive and negative predictive values. To determine how the automated technique compared with inexperienced reviewers of conventional images, these indexes were compared between the two methodologies.

Pairs of repeated measurements obtained in nine patients with peak dose of dobutamine were used to calculate the intrasubject variability of our methodology, which was expressed for each segment as absolute difference between repeated measurements in percent of their mean. The reproducibility data were expressed as mean value for each segment calculated in all nine patients. The lower and higher limits were defined as minimum and maximum variability measured in each segment.

**RESULTS**

Figure 2 shows an example of end-systolic color kinesis images obtained in a patient with normal wall motion. The relative contribution of early colors (orange and yellow) progressively increased with the dose of dobutamine, reflecting increasing endocardial motion during early systole. Although the thickness of the color bands was relatively uniform at rest, reflecting normal wall motion, it increased with dobutamine and remained uniform, reflecting an even augmentation of wall motion.

Figure 3 presents stacked color histograms of regional fractional area change obtained from the images presented in Figure 2. The normal range of regional fractional area change obtained in a group of normal subjects is shown as a dashed band in the background of the histograms obtained at rest (top). In this patient, fractional area change in all segments was within normal limits. The progressively increasing contribution of early contraction with dobutamine dose confirmed in a quantitative manner the positive inotropic effects of this drug.

Figure 4 shows an example of end-systolic color kinesis images obtained in a patient with angiographic evidence of coronary artery disease who developed wall motion abnormalities during dobutamine infusion. The regional wall motion abnormalities noted in this patient at rest were objectively identified as gaps between the individual data and the corresponding normal ranges (Fig. 5, top, open arrows). Dobutamine-induced wall motion abnormalities were objectively detected as >40% reduction in fractional area change in the corresponding segments by comparing the histogram obtained at peak dobutamine with the resting data, which in Figure 5 have been scaled down to 60% of the original value and shown as dotted areas in the background of the peak dobutamine histograms (bottom, solid arrows).

The total number of segments reviewed was 1958 (22 segments in each of 89 patients). Table 1 summarizes the interpretation of regional endocardial motion by expert consensus and by two inexperienced reviewers of conventional gray-scale images without color overlays. In addition, it shows the results of the objective interpretation of regional wall motion based on color kinesis: 1) at rest, by comparing with normal values of regional fractional area change obtained in a group of normal subjects, and 2) with
peak dose of dobutamine infusion, by comparing with each patient's individual data obtained at rest.

**Interpretation of resting images.** At rest, according to the consensus expert interpretation, 1,723 of 1,958 segments were normal (88%), while 235 showed abnormal motion (12%). The inexperienced reviewers correctly identified an average of 1,700 of 1,723 normal (99%) and 178 of 235 abnormal segments (76%), whereas 24 of 1,723 normal segments were incorrectly identified as abnormal (1%) and 58 of 235 abnormal segments were falsely classified as normal (25%). Segmental analysis of color kinesis images correctly identified 1,688 of 1,723 normal (98%) and 192 of 235 abnormal segments (82%), whereas 35 of 1,723 normal segments were incorrectly identified as abnormal (2%) and 43 of 235 abnormal segments were falsely classified as normal (18%).

**Interpretation of peak dobutamine images.** At peak dobutamine infusion, 1,823 of 1,958 segments were classified as normal (93%), and 135 segments were interpreted by expert consensus as showing abnormal endocardial motion (7%). The inexperienced reviewers correctly identified an average of 1,716 of 1,823 normal segments (94%) and only 75 of 135 abnormal segments (56%), whereas 107 of 1,823 normal segments were incorrectly identified as abnormal (6%) and 60 of 135 abnormal segments were falsely classified as normal (44%). The color kinesis-based objective detection of regional wall motion abnormalities yielded the following results: of 1,823 normal segments, 1,792 were correctly identified as such (98%), as well as 103 of 135 abnormal segments (76%), whereas 31 of 1,823 normal segments were incorrectly identified as abnormal (2%) and 32 of 135 abnormal segments were falsely classified as normal (24%).

**Interpretation of response to stress.** Figure 6 shows the distribution of segments according to their wall motion at rest and at peak dobutamine, as well as the type of response to dobutamine. According to the consensus expert interpretation, 1,680 of the 1,958 segments were classified as normal both at rest and peak dobutamine. From 235 segments classified as abnormal at rest, 92 remained abnormal with dobutamine, whereas 143 segments showed appropriate augmentation. Forty-three segments classified as normal at rest showed abnormal wall motion with dobutamine, reflecting drug-induced abnormalities in 23 of 89 patients. Of the 43 segments that showed ischemic response to dobutamine, the inexperienced reviewers correctly identified an average of 9 (21%). In contrast, the objective detection based on analysis of color kinesis images correctly identified
27 of these 43 dobutamine-induced wall motion abnormalities (63%).

**Sensitivity, specificity and accuracy.** Table 2 presents the sensitivity, specificity, accuracy and the predictive values of the interpretation of conventional stress images by the inexperienced reviewers and by the segmental analysis of color kinesis images, both compared with the consensus of experienced readers as a “gold standard.” With peak dose of dobutamine, all values in the table are lower than at rest. It is important to note that the sensitivity, specificity and accuracy of the method based on color kinesis were higher than those of the inexperienced reviewers, both at rest and with dobutamine (Table 2).

**Diagnosis of ischemic response in individual patients.** Table 3 shows the statistics of diagnosis of ischemic response to dobutamine on a patient-by-patient rather than on a segment-by-segment basis. According to the expert consensus interpretation, 11 of 89 patients showed an ischemic response defined as dobutamine-induced wall motion abnormality in at least two contiguous segments in one view or two overlapping segments in two different views. The inexperienced reviewers correctly identified 3 of these 11 patients (27%), and 73 of 78 patients (94%) who did not show ischemic response. However, they failed to detect ischemic response in 8 of 11 patients (73%) and misdiagnosed with ischemic response 9 of the 78 patients (12%). In contrast, the color kinesis-based technique correctly identified 10 of 11 patients who developed ischemic response (91%), and 69 of 78 patients (88%) who did not show ischemic response. This technique missed ischemic response in only 1 of 11 patients (9%), but misdiagnosed with ischemia 9 of the 78 patients (12%). Repeated examination of image sequences showed that these false-positive identifications of stress-induced ischemia were a result of inadequate endocardial visualization and tracking at peak stress.

**Comparisons with coronary angiography.** Sixteen patients (seven men, nine women, mean age 66 ± 4 years) with dobutamine-induced regional wall motion abnormalities underwent subsequent coronary angiography, and total of 352 segments were studied (22 segments in four views in each patient). Based on the findings of coronary angiography, 257 segments were classified as normally perfused, whereas 95 segments were classified as underperfused. Consensus readings of two expert reviewers of gray-scale images confirmed normal wall motion in 217 of 257 normally perfused segments (84%) and detected wall motion abnormalities in 73 of 95 underperfused segments (77%). Regional wall motion abnormalities were detected in an
additional 40 of 257 segments supplied by normal coronary arteries (16%), and 22 of 95 segments showed normal wall motion in the presence of coronary stenosis (23%). Thus, the overall accuracy of the conventional technique versus coronary angiography was 0.82.

Analysis of color kinesis images demonstrated normal wall motion in 246 of 257 normally perfused segments (96%) and detected wall motion abnormalities in 79 of 95 underperfused segments (83%). Regional wall motion abnormalities were detected in an additional 11 of 257 segments supplied by normal coronary arteries (4%), and 16 of 95 segments showed normal wall motion in the presence of coronary stenosis (17%). The overall accuracy of the automated technique versus angiography was 0.93.

Reproducibility. Figure 7 shows the results of variability calculated by analyzing repeated measurements. In most segments, the variability ranged between single digits and around 30%, with mean values between 15% and 20%.

DISCUSSION

Exercise echocardiography is a stress-imaging modality used for the detection of ischemic regional wall motion abnormalities and the diagnosis and prognosis of CAD. It has the advantages of versatility, portability, low cost and immediate results (2). Echocardiographic exercise stress testing was reported to have high sensitivity in detecting CAD (18–26). A significant limitation of this technique is that exercise-induced regional wall motion abnormalities may resolve rapidly, which requires image acquisition within 1 min of

![Figure 5](image-url)  
Figure 5. Stacked color histograms of regional fractional area change obtained from images in Figure 4. The normal range of regional fractional area change shown as a dashed band in the background of the resting histograms allowed objective identification of the regional wall motion abnormalities noted in this patient at rest (top, open arrows). The resting histograms, scaled down to 60% and shown as dotted areas in the background of histograms obtained with dobutamine, allow objective detection of stress-induced wall motion abnormalities (bottom, solid arrows) in the perfusion territory of the left anterior descending coronary artery.

![Figure 6](image-url)  
Figure 6. (Top) schematic distribution of segments according to their wall motion at rest and at peak dobutamine, as well as the type of response to dobutamine, according to the consensus interpretation of two experienced reviewers. (Bottom) Segments that showed ischemic response to dobutamine were classified by the inexperienced reviewers and by the analysis of color kinesis images. Open bars: normal wall motion; dotted bars: abnormal wall motion.
the termination of exercise. In addition, some patients are unable to walk on a treadmill or perform bicycle exercise for different reasons such as orthopedic limitations, peripheral vascular disease, advanced age, pulmonary disease or neurologic deficits. These patients are evaluated using pharmacologic agents that increase myocardial oxygen consumption, such as synthetic catecholamine dobutamine (3).

Dobutamine stress echocardiography, a relatively new methodology, has become a powerful addition to the diagnostic and prognostic tools available for the noninvasive detection of ischemic heart disease (19,27,28), identification of viable myocardium (29), assessment of patients after myocardial infarction (30), thrombolysis (29), coronary artery bypass graft surgery or percutaneous transluminal coronary angioplasty (31). The high sensitivity and specificity of dobutamine stress echocardiography in detecting coronary disease have been established in multiple studies (18,19,21,28,32–35).

However, the major weakness of both exercise and pharmacologic stress echocardiography is that conventional clinical assessment of LV endocardial wall motion and myocardial thickening is based on visual interpretation, which is subjective and experience dependent. Picano et al. (36) demonstrated that the diagnostic accuracy of stress echocardiography is highly dependent on the experience of the interpreting physician. The sensitivity, specificity and accuracy of the interpretations made by inexperienced reviewers were lower than those of experienced readers. Thus, the need for easy and objective techniques to evaluate regional left ventricular function has become more obvious with the growing popularity of pharmacological stress testing in echocardiography.

Because the subjective nature of the two-dimensional echocardiographic interpretation of ventricular wall motion has been recognized even before the advent of stress protocols, multiple studies used different methods to improve the objectivity of this methodology (6–11). However, these techniques were based on time-consuming, offline, frame-by-frame tracing of endocardial borders, and therefore remained subjective and impractical for routine clinical use. Other computerized techniques either required extensive offline processing (37,38) or were limited to specific imaging planes (39,40). Recently, new techniques, such as color-enhanced motion analysis and tissue Doppler imaging, have been shown to have the potential to objectively assess regional LV function (41,42), however, the clinical value of these techniques in conjunction with stress testing has not yet been definitively established (41,43). Also, the use of harmonic imaging, with or without contrast agents, may prove useful because these techniques have been shown to improve endocardial visualization and thus may facilitate the evaluation of endocardial motion in the echocardiographic stress setting.

The development of automated boundary detection based on acoustic quantification (44) allowed continuous real-time measurements of LV cross-sectional area throughout the cardiac cycle, obviating the need for manual tracing of the endocardial boundary to assess global ventricular function.

### Table 1. Interpretation of Regional Endocardial Motion

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<thead>
<tr>
<th></th>
<th>Rest</th>
<th>Peak Dobutamine</th>
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<tbody>
<tr>
<td></td>
<td>TP</td>
<td>FN</td>
</tr>
<tr>
<td>Standard</td>
<td>235</td>
<td></td>
</tr>
<tr>
<td>Inexp. 1</td>
<td>160</td>
<td>75</td>
</tr>
<tr>
<td>Inexp. 2</td>
<td>195</td>
<td>40</td>
</tr>
<tr>
<td>Inexp. mean</td>
<td>178</td>
<td>58</td>
</tr>
<tr>
<td>Color kinesis</td>
<td>192</td>
<td>43</td>
</tr>
</tbody>
</table>

Consensus of two experienced readers (standard) was compared with two inexperienced reviewers of conventional gray-scale images obtained at rest and with peak dose of dobutamine infusion. The results of objective interpretation of regional wall motion using segmental analysis of end-systolic color kinesis images were obtained: 1) at rest, by comparisons with normal values of regional fractional area change obtained in a group of normal subjects; and 2) under peak dose of dobutamine infusion, by comparisons with each patient’s individual data obtained at rest. The numbers indicate segments; interpretations are compared versus the standard.

FN = false negative, FP = false positive, Inexp. = inexperienced readers, TN = true negative, TP = true positive.

### Table 2. Statistics of Agreement of the Conventional Interpretation of Gray-scale Images by the Inexperienced Reviewers and the Objective Evaluation of Regional Endocardial Motion Based on Segmental Analysis of Systolic Color Kinesis Images

<table>
<thead>
<tr>
<th></th>
<th>Rest</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Sensitivity</td>
<td>Specificity</td>
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<tr>
<td>Inexp. 1</td>
<td>0.68</td>
<td>0.98</td>
</tr>
<tr>
<td>Inexp. 2</td>
<td>0.83</td>
<td>0.99</td>
</tr>
<tr>
<td>Inexp. mean</td>
<td>0.76</td>
<td>0.98</td>
</tr>
<tr>
<td>Color kinesis</td>
<td>0.82</td>
<td>0.98</td>
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</table>

Both techniques are compared with a consensus interpretation of two experienced reviewers of conventional gray-scale images. Inexp. = inexperienced readers, NPV = negative predictive value, PPV = positive predictive value.
Table 3. Diagnoses of Ischemic Response to Dobutamine on a Patient-by-Patient Basis Made by Two Inexperienced Reviewers of Conventional Gray-scale Images, and the Objective Technique Based on Color Kinesis

<table>
<thead>
<tr>
<th></th>
<th>TP</th>
<th>FN</th>
<th>FP</th>
<th>TN</th>
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<tr>
<td>Gold standard</td>
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<td>78</td>
</tr>
<tr>
<td>Inexp. 1</td>
<td>3</td>
<td>8</td>
<td>8</td>
<td>70</td>
</tr>
<tr>
<td>Inexp. 2</td>
<td>3</td>
<td>8</td>
<td>10</td>
<td>68</td>
</tr>
<tr>
<td>Inexp. mean</td>
<td>3</td>
<td>8</td>
<td>9</td>
<td>69</td>
</tr>
<tr>
<td>Color kinesis</td>
<td>10</td>
<td>1</td>
<td>9</td>
<td>69</td>
</tr>
</tbody>
</table>

Both techniques are compared with the consensus interpretation of two experienced readers (standard). The numbers indicate patients.

FN = false negative, FP = false positive, Inexp. = inexperienced readers, TN = true negative, TP = true positive.

More recently, the ability of a related technique, color kinesis, has been evaluated by several groups as an aid for the evaluation of regional wall motion (45–48). We have previously described a method of segmental analysis of color kinesis images, which provides quantitative indices of magnitude and timing of regional LV endocardial motion (13). This technique has been used to objectively identify systolic wall motion abnormalities in patients with coronary artery disease at rest (14), and regional filling asynchrony in patients with diastolic dysfunction due to LV hypertrophy (15) and dilated cardiomyopathy (49). We have also previously studied the inter- and intraobserver variability of segmental analysis of resting color kinesis images (14,50). This study was designed to determine the applicability of using this technique in consecutive patients referred to our laboratory for routine clinical stress testing.

Segmental analysis of color kinesis images obtained in this group of consecutive patients allowed us to objectively identify stress-induced regional wall motion abnormalities. Regional fractional area change histograms were obtained in each patient at rest and then used as an individual reference for comparisons with peak dobutamine data. This approach allowed us to avoid the need to establish normal values in different populations with dobutamine. Our results showed that this objective automated method had fewer false-negative and false-positive identifications of wall segments compared with inexperienced readers of conventional images, both at rest and even more so with dobutamine (Table 1). Accordingly, this method had higher sensitivity, specificity and accuracy, especially at peak dobutamine (Tables 1 and 2), which is known to be more difficult to interpret due to altered heart rate and contractility.

Our automated technique correctly identified 63% of segments that showed stress-induced wall motion abnormality, reflecting a threefold difference compared with inexperienced reviewers of stress tests who identified only 21% of these segments. We also found that 10 of 11 patients who developed ischemic response in at least two wall segments were correctly identified by the objective technique, whereas only three were diagnosed by inexperienced reviewers (Table 3).

We did not calculate sensitivity, specificity and accuracy of this new technique on a patient-by-patient basis because a larger patient population would be required, in particular, patients who developed ischemia under pharmacologic stress. However, our results proved the feasibility of applying this new technique to consecutive patients referred for pharmacologic stress echocardiography and objective detection of dobutamine-induced regional wall motion abnormalities.

Study limitations. The use of a consensus of two expert readers of stress echocardiograms, rather than another well-established technique, as a gold standard to which both the readings of the inexperienced reviewers and the automated interpretations were compared, requires discussion. Indeed, previous studies used coronary angiography to establish the accuracy and experience dependency of the conventional dobutamine stress testing in the diagnosis of CAD (18). However, the focus of our study was the question whether quantitative segmental analysis of color kinesis images can provide more sensitive, specific and accurate detection of stress-induced wall motion abnormalities than inexperienced reviewers of conventional images obtained in unselected patients. In fact, comparisons with angiography could not directly answer this specific question for several reasons. First, coronary stenosis does not necessarily result in stress-induced wall motion abnormalities. Second, even in the presence of confirmed coronary stenosis, it is difficult to determine which segments should be affected. And, third, because angiography data are mostly available in patients who show an ischemic response to stress, the choice of angiography as a gold standard would have introduced a strong postreferral bias (2), and would thus have hampered the evaluation of our technique in consecutive patients.

Nevertheless, to test the ability of this new technique to diagnose coronary artery disease, data obtained in a subgroup of patients who developed regional wall motion abnormalities were compared with the findings of coronary angiography on a segment-by-segment basis. These comparisons showed high level of agreement between angiography and automated detection of dobutamine-induced wall

Figure 7. Reproducibility of segmental analysis of color kinesis images obtained with peak dose of dobutamine infusion. Variability was calculated for each segment as absolute difference of repeated measurements in percent of their mean. Data are presented as mean of nine patients (dark bars) with the extreme values measured (light bars).
motion abnormalities, which, in this small group of patients, was even higher than the diagnostic accuracy of conventional visual interpretation of dobutamine stress echocardiography when compared with coronary angiography. Nevertheless, the results of this study should in no way be interpreted such that individuals who are not sufficiently trained to interpret echocardiography may consider involving themselves with stress testing as long as they use a supplemental technique such as quantitative color kinesis.

Acquisition of color kinesis images during stress testing is more technically challenging than in the nonstress setting. Although gain settings, optimized for endocardial tracking at rest, were saved and retrieved during subsequent phases of the protocol, they frequently had to be quickly readjusted, especially at peak dobutamine when optimal endocardial tracking was at times difficult to achieve. These readjustments of gain settings typically did not prolong the protocol because they were performed before patients reached their target heart rate and images were acquired for the next protocol phase. Nevertheless, data were obtained in all patients who had sufficiently good image quality to allow automated endocardial tracking, without excluding any patients based on the quality of their color kinesis images. This proved the feasibility of obtaining color kinesis images in consecutive patients undergoing stress testing.

In previous studies, to improve the accuracy of our measurements, we averaged data obtained from several heartbeats (13–15). This strategy could not be applied in this protocol due to the limitations of the commercial system, which allows acquisition of only one beat per protocol phase in each view. The performance of the objective technique could probably be further improved had it been possible to acquire multiple heartbeats and average data. The low temporal resolution of color kinesis (30 frames/s) may not allow the definition of endocardial motion at high heart rates accurate enough to obtain indexes, such as velocity of endocardial motion. However, this factor was only of limited significance in this study, because overall systolic extent of regional wall motion, and not its timing, was analyzed.

Summary. We found that systolic color kinesis images can be obtained during dobutamine stress echocardiography in consecutive patients. Quantitative segmental analysis of these images allows objective detection of stress-induced wall motion abnormalities, which is more sensitive, specific and accurate than inexperienced readers of conventional stress echocardiograms. The objective and quantitative aspects of this technique are of particular clinical value in pharmacologic stress testing, because images obtained with dobutamine are often more difficult to interpret and require even more expertise than resting echocardiograms. These findings may eventually have significant clinical bearing because many institutions do not have the volume of studies performed to allow for the level of specific expertise that the reviewers at our laboratory are able to achieve. Our results demonstrated that this new quantitative technique for objective detection of stress-induced regional wall motion abnormalities is simple and quick, and may therefore have clinical value in assessing myocardial risk.

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