Myocardial Tissue Characterization After Acute Myocardial Infarction With Wavelet Image Decomposition

A Novel Approach for the Detection of Myocardial Viability in the Early Postinfarction Period

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Background—Only a few texture measures can be used for texture characterization of infarcted myocardium and detection of reperfused myocardium early after infarction. This study was conducted to establish the relationship between texture properties of infarcted myocardium and infarct-related artery patency by quantitative computer analysis of 2-dimensional echocardiographic images with the wavelet-based method for texture characterization, evaluate the relationship between texture properties and myocardial viability, and correlate histopathologic changes after experimental infarction with the texture measures.

Methods and Results—We analyzed 2-dimensional transthoracic echocardiographic images in 18 patients at different time points after infarction using the wavelet transform method. Regional wall motion of infarcted segments was analyzed on a follow-up echocardiographic study obtained 6 months after infarction. To verify the accuracy of the proposed texture measure and energy difference cutoff value, we prospectively evaluated another group of 19 patients. In addition, histopathologic changes in 9 dogs with experimental infarction were correlated with the texture measures. Sensitivity, specificity, and accuracy of the wavelet method for detection of reperfusion in the study group were 73%, 86%, and 78%, respectively, on day 2; 91%, 86%, and 89%, at 1 week; and 100%, 100%, and 100% at 3 weeks. Among 9 patients with improvement in regional wall motion on a follow-up study, 7 on day 2, 8 at 1 week, and 9 at 3 weeks were classified into the reperfused group by the wavelet method. Histopathologic features associated with the classification of reperfusion by the wavelet method were infarct transmurality (P=0.024) and degree of necrosis (P=0.028).

Conclusions—Our clinical and experimental data suggest that the wavelet method can be used to differentiate between viable myocardium with recovery potential and definite myocardial necrosis in the early postinfarction period.

(Circulation. 1998;98:634-641.)

Key Words: myocardial infarction n reperfusion n tissue

Several studies have demonstrated that myocardial infarction produces alterations in myocardial tissue structure and composition,1 leading to changes in acoustical properties of the myocardium. However, with standard 2-dimensional echocardiographic examination, it is impossible to differentiate nonfunctional infarcted myocardium with an occluded infarct-related artery from reperfused, stunned, or hibernating myocardium, which can recover either spontaneously or after appropriate therapeutic interventions. Furthermore, detection of a patent infarct-related artery by coronary angiography is not sufficient evidence that dysfunctional myocardium perfused by this artery is still viable. Because the quality of standard ultrasound images precludes accurate identification of myocardial reperfusion early in the course of myocardial infarction, the search for additional sources of information is still in progress.

We2 have previously shown that only a few texture measures can be used for texture characterization of infarcted myocardium and detection of reperfused myocardium in the early postinfarction period. Among these, measures calculated with the wavelet image decomposition method revealed the best preliminary results2 and therefore were selected for

Received September 24, 1997; revision received March 11, 1998; accepted April 20, 1998.
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the current study. To the best of our knowledge, no studies have assessed the application of the wavelet transform method for detection of reperfused or viable myocardium early after myocardial infarction.

The purposes of this study were as follows: (1) to establish the relationship between texture properties of the infarcted myocardium and patency of the infarct-related artery by use of quantitative computer analysis of 2-dimensional echocardiographic images with the wavelet-based method for texture characterization; (2) to evaluate the relationship between texture properties and myocardial viability, as assessed by follow-up echocardiograms 6 months after infarction; and (3) to correlate histopathologic changes after experimental infarction with the texture measures.

Methods

Study Patients

The study group consisted of 18 patients with first acute myocardial infarction (11 with a patent and 7 with an occluded infarct-related artery) taken from our acute myocardial infarction database.

Data Acquisition

We retrospectively analyzed 2-dimensional echocardiographic images obtained 2 days, 1 week, and 3 weeks after infarction. All images were acquired on a commercially available imaging system (Acuson 128) with a 2.5-MHz probe and recorded on 0.5-in VHS videotapes. All recordings were made by 2 echocardiographers; each was free to set the time-gain compensation, gain, and adjustment during the recording to optimize images visually. Depending on infarct location, end-diastolic images from apical 4- and 2-chamber views were used for data acquisition. Images recorded on videotapes were digitized with 512×512 pixel and 256-gray-level resolution. As an input into the texture analysis procedure, for each patient 5 samples of 16×16 pixels were taken from the infarcted area of the myocardium and 5 from the area not affected by infarction (Figure 1). For this purpose, asynergic segments were considered an infarcted zone. In a given patient, tissue samples were taken from the same segments (initially assigned as infarcted and normal). Samples were taken by the electrical engineer in cooperation with experienced echocardiographers who were blinded to patients’ clinical and angiographic data. All texture analysis and calculations were done by the engineer team, without any knowledge of patients’ history.

Coronary Angiography

Coronary angiography was performed in all patients before discharge. Perfusion of the infarct-related artery was assessed by use of Thrombolysis In Myocardial Infarction (TIMI) criteria.³ Successful reperfusion of the infarct-related artery was defined as TIMI grade 3.

Texture Analysis

For calculation of the texture measures, we performed an image decomposition with filter banks derived from wavelet functions (Figure 2).³ After thorough mathematical analysis,³ we selected energy calculated from the vertical-edge image (ENG VH) as the texture measure to be used in further classification.

Classification

For each analyzed patient, 5 tissue samples each were taken from the area not affected by infarction and from infarcted myocardial segments. Energy was computed for each sample. As a quantitative measure of dissimilarity between 2 tissue groups (ie, between normal and infarcted tissue), we have proposed the distance function (D):

\[ D = \sqrt{\frac{(x_1 - x_2)^2}{C_1 + C_2}} \]

where \( x_1 \) and \( x_2 \) are the texture measure mean values for the tissue samples taken from normal tissue and infarcted area, respectively; \( n_1 \) and \( n_2 \) are numbers of tissue samples taken from normal tissue and infarcted area, respectively; and \( C_1 \) and \( C_2 \) are the texture measure variances for normal and infarcted tissue, respectively.

When tissue samples taken from infarcted myocardium and from areas not affected by infarction are composed from similar textural patterns, the random variables \( x_1 \) and \( x_2 \) have similar distributions, and the distance between them (value of the \( D \) function) is very small. On the contrary, when analyzed samples have definite dissimilarity, the variables \( x_1 \) and \( x_2 \) have significantly different distributions, and the distance between them will have higher values. Thus, in this case, \( D \) represents the quantitative measure of similarity between normal and infarcted tissue. With the automatically determined³ \( D \) cutoff value of 5.5, infarcted myocardium was classified as reperfused (≤5.5) or nonreperfused (>5.5).

Validation of the Wavelet Method

To assess the applicability of the proposed texture measure and energy difference cutoff value in differentiating patients with and without reperfusion, we prospectively evaluated another group of 19 patients (10 with a patent and 9 with an occluded infarct-related artery) using the same texture measure and the same \( D \) cutoff value. To examine the impact of image quality and various storage conditions, we analyzed images of 10 healthy volunteers and 10 patients (5 with a patent and 5 with an occluded infarct-related artery) obtained directly from the echocardiograph and the videotape (Appendix).

Figure 1. Data acquisition. Transthoracic echocardiogram, apical 4-chamber view. White and black squares represent samples taken from the normal and infarcted myocardium, respectively.

Figure 2. Block diagram of the filter bank performing 2-dimensional wavelet decomposition. The input into the filter bank is the original textured image (\( f_{\text{LH}} \)). Low-pass and high-pass filters performing the decomposition are denoted with \( L \) and \( H \), respectively. At the output of the filter bank are 4 decomposed images (\( f_{\text{LL}}, f_{\text{LH}}, f_{\text{HL}}, \) and \( f_{\text{HH}} \)).
Assessment of Viability
Because we have previously shown that regional wall motion of the infarcted zone after thrombolysis improves up to 3 months after infarction, all patients underwent follow-up echocardiographic study 6 months after infarction to evaluate the relationship between texture properties and myocardial viability. For each study, wall motion was graded as normal, hypokinetic, akinetic, or dyskinetic and improvement, deterioration, or no change of regional wall motion of the infarcted area was noted. Improvement in regional wall motion of the analyzed segments in the infarcted zone over time was considered evidence of the viability of these segments. It was considered that viability was successfully predicted by the wavelet method if the patient was classified into the reperfused group and subsequent improvement in regional wall motion was noted on a follow-up study.

Experimental Study
Finally, to assess the relationship between histopathology and the texture measures, we evaluated 11 dogs with experimental myocardial infarction. The left anterior descending coronary artery distal to the first diagonal branch was ligated and tightened to occlude the artery. Dogs were divided into 2 groups: those with permanent occlusion of the left anterior descending artery (5 dogs) and those with reperfusion after 60-minute occlusion (6 dogs). The echocardiographic protocol was the same as for the patients: 2-dimensional echocardiographic images were obtained on day 2 and at 1 and 3 weeks after experimental infarction. Images were captured directly from the echocardiograph and were analyzed in the same manner as for the patients. Classification of the infarcted segments as reperfused or nonreperfused was done with the same cutoff value as for the patients. Two dogs (1 with permanent occlusion and 1 with reperfusion) died before the end of the experiment and were excluded from the study analysis.

Immediately after the echocardiographic examination at 3 weeks, dogs were killed, and the hearts were subjected to histopathologic examination. An infarcted segment that was equidistant from the center of infarction and from normal surrounding myocardium was analyzed in both occluded and reperfused dogs. Samples were paraffin-embedded and sections stained by hematoxylin-eosin, Mason’s trichrome, and elastica–Van Gieson. The following histopathologic features were graded with a semiquantitative scoring system: transmurality of an infarct, degree of necrosis, degree of fibrosis (collagen content), and ratio of necrotic to preserved capillaries. Transmurality was scored as 1 (infarct <50% of wall thickness), 2 (infarct >50% of wall thickness), or 3 (100% of wall thickness was infarcted). Degree of necrosis was graded by measuring the extent of necrosis in 20 randomly chosen high-power fields (×400) as follows: none (score = 0) if there was no necrosis and mild (score = 1), moderate (score = 2), or severe (score = 3) if ≤33%, ≤66%, or >66%, respectively, of the total area examined was necrotic. The degree of fibrosis was graded with the same grading system: none (score = 0), mild (score = 1), moderate (score = 2), or severe (score = 3). If all capillaries within an examined area were preserved, the score was 0; if ≤33% of capillaries were necrotic; the score was 1; if ≤66% of capillaries were necrotic, the score was 2; and if >66% of capillaries were necrotic, they were scored as 3.

Statistical Analysis
Mann-Whitney U test was used to test the differences in distance measures between patients with patent and occluded infarct-related arteries, as well as to test the relationship between classification results by the wavelet method and different histopathologic features in the experimental study. Analysis of distance measure changes over time was performed by 2-way ANOVA, and the relationship between distance measure and wall motion of the infarcted zone over time (with wall motion as a covariate) was analyzed by repeated-measures ANOVA.

Results
Texture Properties of Infarcted Myocardium and Patency of Infarct-Related Artery
Figures 3 and 4 show the application of the wavelet method to nonreperfused and reperfused myocardial tissue, respectively. With nonreperfused myocardium (Figure 3), a clear
difference between the normal (Figure 3a) and infarcted area (Figure 3b) can easily be seen. In all cases, the most prominent difference was detected in the vertical-edge image \( f^{LH} \). However, no difference was noted between the normal and infarcted area in reperfused myocardium (Figure 4).

### Differentiation of Patients With and Without Reperfusion

Distance measures for the study and validation groups are shown in Table 1. Texture data for the energy measure calculated from vertical-edge images, as well as the relationship between classification results and perfusion status for all patients, are shown in Tables 2 and 3. A significant decrease of the distance measure over time occurred in reperfused (\( \chi^2=6.95, \ P=0.03 \)) but not in nonreperfused (\( \chi^2=0.88, \ P=0.65 \)) patients. Repeated-measures ANOVA that included all patients revealed that regional wall motion changes over time had no impact on distance measures (F=0.21, \( P=0.65 \)). Sensitivity, specificity, accuracy, and positive and negative predictive values of the wavelet method for the detection of reperfusion in both the study and validation groups are shown in Figure 5a and 5b.

### Viability

On a follow-up study 6 months after infarction, 9 patients in the study group and 8 in the validation group showed improvement in regional wall motion of infarcted segments over time or after revascularization procedures (2 patients from the study group and 4 from the validation group underwent CABG surgery), indicating the presence of viable

### Table 1. Distance Values Between Normal and Infarcted Zones

<table>
<thead>
<tr>
<th>Study group</th>
<th>Day 2</th>
<th>1 Wk</th>
<th>3 Wk</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6.04±6.61</td>
<td>9.78±4.98</td>
<td>2.38±2.79</td>
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<tr>
<td></td>
<td>2.87±4.22</td>
<td>25.52±23.1*</td>
<td>2.72±3.29</td>
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<tr>
<td>All patients</td>
<td>4.53±5.7</td>
<td>18.63±18.97*</td>
<td>2.54±2.96</td>
</tr>
</tbody>
</table>

All values are mean±SD.

*\( P<0.05 \), † \( P<0.001 \) between patients with patent and occluded infarct-related arteries.

### Table 2. Texture Measures and Classification Results for Patients With Patent Infarct-Related Arteries

<table>
<thead>
<tr>
<th>Study group</th>
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<th>1 Wk</th>
<th>3 Wk</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Normal</td>
<td>Infarct</td>
<td>( D )</td>
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<tr>
<td></td>
<td>60.7±10.1</td>
<td>16±2.3</td>
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<td></td>
<td>11.6±1.5</td>
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</tr>
<tr>
<td></td>
<td>18.8±4.6</td>
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<td></td>
<td>21±5.8</td>
<td>15.6±2.1</td>
<td>1.96</td>
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<td>21±2.7</td>
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<td></td>
<td>61.1±6.9</td>
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<td>0.53</td>
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<td></td>
<td>77.6±5.4</td>
<td>12.2±2.7</td>
<td>5.7</td>
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<tr>
<td></td>
<td>88.4±6.7</td>
<td>81.1±11.5</td>
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<td>81.1±2.5</td>
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</table>

\( D \) indicates distance function value; \( p \), patients with patent infarct-related arteries. Boldface indicates classification results discordant with vessel patency. Texture measures are expressed as mean±SD.
myocardium; each of them had a patent infarct-related artery. Patients with an occluded infarct-related artery showed no improvement in regional wall motion of the infarcted segments. Sensitivity, specificity, accuracy, and positive and negative predictive values of the wavelet method for detection of viability in both the study and validation groups are shown in Table 4. On the other hand, nonviability was correctly predicted in 17, 18, and 15 of 20 patients on day 2, on day 7, and at 3 weeks, respectively.

**Experimental Study**

Histopathologic findings are shown in Table 5. Texture measures calculated from vertical-edge images, as well as the relationship between classification results and perfusion status for all dogs, are shown in Table 6. Sensitivity, specificity, and accuracy of the wavelet method for the detection of reperfusion were 100%, 50%, and 78%, respectively, on day 2; 80%, 75%, and 78% at 1 week; and 80%, 100%, and 89% at 3 weeks. Histopathologic features found to be related to classification results by the wavelet method were transmurality of an infarct (P=0.024) and degree of necrosis (P=0.028). However, the density of preserved capillaries (P=0.18) and collagen content (P=0.58) did not correlate with the classification results.

**Discussion**

It has been reported that infarct-related artery patency has numerous beneficial effects: it improves healing of the infarcted tissue and prevents infarct expansion and left ventricular remodeling.6–8 preserves viability of hibernating myocardial segments,9 and increases electrical stability.10 To plan management strategy in the postinfarction period, it is important to determine infarct-related artery patency and whether infarcted segments are viable or dead. Although there are several noninvasive markers of successful reperfusion, they are not specific and reliable enough to enable definite conclusions to be reached.11 Coronary angiography yields an accurate assessment of vessel patency but does not provide any information about infarcted tissue properties. On the other hand, viability can be assessed by low-dose dobutamine or dipyridamole echocardiography, PET, or follow-up echocardiographic or radionuclide ventriculography studies (detecting functional improvement of previously asynergic segments that occurs spontaneously or after revascularization procedures). However, there is still a need for an additional method that could provide valuable information regarding myocardial perfusion and viability simply and noninvasively; texture characterization of the affected myocardium is an attractive approach.

In the image-processing field, a number of methods for texture characterization have been developed over the years.2,12 Some of these techniques have been used in medicine for the assessment of different pathological conditions of the myocardium.1 For example, recently it has been shown that short-lasting myocardial ischemia is associated with an abrupt increase in myocardial echodensity detectable by videodensitometric analysis applied to standard transthoracic echocardiographic images.13 Also, it has been shown that the cyclic variation of relative integrated backscatter can be used to diagnose recent myocardial infarction.14 Additionally, ul-

### Table 3. Texture Measures and Classification Results for Patients With Occluded Infarct-Related Arteries

<table>
<thead>
<tr>
<th>Patient</th>
<th>Normal</th>
<th>Infarct</th>
<th>D</th>
<th>Normal</th>
<th>Infarct</th>
<th>D</th>
<th>Normal</th>
<th>Infarct</th>
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</tr>
<tr>
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<tr>
<td>4o</td>
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<td>9.99</td>
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<td>93±12</td>
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<td>46.9±4.0</td>
<td>11.3</td>
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</table>

*D* indicates distance function value; 0, patients with occluded infarct-related arteries. Boldface indicates classification results discordant with vessel patency. Texture measures are expressed as mean±SD.
trasonic tissue characterization was used successfully for diagnosis of acute myocardial infarction in the coronary care unit, showing results comparable to standard 2-dimensional echocardiography. However, data are scarce regarding the application of texture characterization for detection of the extent of irreversibly damaged myocardium in humans. Furthermore, to the best of our knowledge, the value of the wavelet transform method for assessment of viability early after myocardial infarction has not been established.

Our data demonstrate that in the majority of patients, no difference in myocardial texture existed between normal segments and reperfused infarcted segments, whereas a significant difference between normal myocardium and non-reperfused infarcted segments was found. In addition, the majority of patients classified as reperfused by the wavelet method showed regional functional improvement on follow-up studies, indicating that functional recovery of infarcted segments can be predicted by this method. Therefore, it appeared that this method had potential to detect viable myocardium early in the postinfarction period, providing additional information compared with serial observation of regional wall motion improvement over time.

Initial evaluation of the method and classification were based on the perfusion status of the myocardium. It is reasonable to expect that the majority of patients with reperfusion have different amounts of viable myocardium in the infarct zone; however, reperfused myocardium is not necessarily viable. To clarify what we really detect by the wavelet method (ie, what is the histopathologic correlate of the energy difference between reperfused and nonreperfused myocardium detected by the wavelet method), we conducted the experimental study. The analysis we performed revealed that the histopathologic features that have a major impact on accurate differentiation between reperfused and nonreperfused myocardium by the wavelet method were infarct transmurality and the degree of necrosis. Therefore, it appears that this method may differentiate nontransmural infarcts with mild to moderate necrosis, containing different amounts of viable myocardium, from transmural, severely necrotic infarcts without viable tissue. Because reperfused myocardium shows less necrosis and less transmurality, on the basis of our experimental and clinical data, it is more likely that the energy difference between reperfused and nonreperfused segments detected by the wavelet method reflects viability as a consequence of reperfusion but not the reperfusion itself. There were patients with a patent vessel in whom akinesis persisted throughout the study, and yet there was a reduction in energy difference, suggesting myocardial viability. It may be assumed that myocardial structure and composition in these patients were preserved such that the differences in acoustic properties and texture between infarcted and normal segments were not significant, indicating presumably hibernating myocardial segments.

**Technical Considerations**

A method for successful characterization of myocardial tissue changes caused by infarction must be sensitive to detect minor changes in intracellular structure and myocardial fiber orientation. In addition, it must be relatively insensitive to the quality of the echocardiographic equipment, variability of gain settings and adjustment, and the expertise of technicians performing the 2-dimensional echocardiographic study. Another disadvantage is the relatively poor quality of ultrasound...
images.2,16 Through numerous experiments with the different texture measures, we have concluded that for analysis of myocardial tissue, the wavelet-based approach performs better than other techniques.2,3 Furthermore, ultrasound noise is a random phenomenon, mostly affecting a single image point. Therefore, of all images obtained through wavelet decomposition, the corner image f’h’ (representing the highest frequencies) is the most sensitive to noise. Because we do not use the energy ENGhth, the results are also applicable in the presence of noise or any high-frequency, localized distortion. An important reason for the good performance of the proposed method is the unsupervised nature of the classification scheme, in which the decision whether reperfusion occurred or not was made by comparison of only the tissue samples taken from the same image. Therefore, changes of the gain and processing settings throughout the study could not affect the results. Additionally, reperfusion was not determined from the numerical values of texture measures directly but was expressed through the value of the distance function, representing the similarity between normal and infarcted tissue. By using this classification criterion, we have made the algorithm insensitive to the acoustic variability of analyzed images. There are several additional reasons why wavelet-based texture analysis may be adequate for application in this setting. It has been shown that the wavelet transform is a powerful analytical tool for analyzing singularities in processes.3,17 The visual difference between normal and infarcted myocardial tissue is barely distinguishable because of minor changes in intracellular structure; the wavelet transform is appropriate for “zooming in” these differences. Also, the wavelet transform represents an image decomposition into 4 different orientations (Figures 2 through 4), which is an excellent way to study myocardial fiber orientation.

**Study Limitations**

Texture characterization is highly dependent on the selection of texture description operators, as well as on the selection and quality of images and myocardial texture samples. In standard ultrasound images, the most important characteristics of a given picture, such as brightness, contrast, or texture, change along the abscissa and ordinate. Some of these inequalities can be removed by image-processing techniques. However, in this application, during the selection of representative tissue samples for 1 class, it is strongly desirable to take image samples only from an isolated myocardial region, without great changes in cursor positions. Otherwise the variability between texture measures calculated for a single class could affect classification results. Additionally, the proposed method is based on comparison to the wall that is clearly uninvolved in infarction, which would probably make its application more difficult in patients suffering from multi-infarct coronary artery disease.

**Conclusions**

Myocardial tissue characterization by use of wavelet image decomposition represents a novel approach for noninvasive assessment of viability of the infarcted myocardium in the early postinfarction period. Our clinical and experimental data suggest that this method can be used for early differentiation between viable myocardium with recovery potential and definite myocardial necrosis. However, additional studies are necessary to confirm these findings.

**Appendix**

**Impact of Storage Conditions on Texture Analysis**

To check the sensitivity of texture measures to the image quality, noise, and videotaping, we analyzed a group of 10 healthy volunteers, capturing the same images both directly from the echocardiograph (“direct images”) and the videotape (“video images”). We took 30 samples from the top to the bottom of the image (from the same positions in both images) and calculated ENGth and texture ENGth measures. By comparing the values obtained from video and direct images, we observed the following: (1) In both images, the variance of the ENGth measure was higher than the variance of ENGth (proving the selection of this measure as a more reliable descriptor). This result was expected because the characteristic ultrasound pattern exhibits different behavior along the path of the acoustic pulse, resulting in prominently different distribution of horizontal edges along the y axis of an image. (2) Because the videotaping induces some blurring, texture measures calculated from video images had consistently smaller values. (3) As a result of the speckle noise and other stochastic problems, both ENGth and ENGth measures had higher variance in direct images. Due to the low-pass-
appears that the method is generally applicable, but processing patients, and 5 of 5 were diagnosed as nonreperfused. Therefore, it images of 3.5 was established, reperfusion was detected in 4 of 5 tentatively smaller in direct images. When a new cutoff value for direct that the distance between normal and infarcted tissue was consis-
6 of 5 were diagnosed as nonreperfused. However, it was observed
3 of 5 were diagnosed as nonreperfused. When analyzing tissue samples taken from the same positions in directly obtained images, we detected reperfusion in 4 of 5 patients, whereas 10 patients were analyzed, 5 with a patent and 5 with an occluded infarct-related artery. On video images with the
1o
21.68 ± 2.16
19.97 ± 1.91
1.32

2o
11.51 ± 2.75
5.42 ± 0.58
4.85

3o
11.52 ± 0.78
3.34 ± 0.37
21.19

4o
12.81 ± 1.67
2.83 ± 0.64
12.48

5p
9.67 ± 1.40
9.45 ± 1.84
0.21

6p
25.40 ± 2.44
19.29 ± 2.52
3.89

7p
32.73 ± 8.78
26.08 ± 1.57
1.67

8p
14.97 ± 0.69
12.74 ± 2.10
2.25

9p
19.48 ± 2.92
13.82 ± 2.70
3.18


D indicates distance function value; o, dogs with occluded infarct-related arteries; and p, dogs with patent infarct-related arteries. Boldface indicates classification results discordant with vessel patency. Texture measures are expressed as mean ± SD.

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Circulation. 1998;98:634-641
doi: 10.1161/01.CIR.98.7.634

Circulation is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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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:
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