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Quantitative texture analysis in two-dimensional echocardiography: application to the diagnosis of experimental myocardial contusion

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ABSTRACT We postulated that the analysis of regional image texture in two-dimensional (2D) echocardiograms would be an accurate method to differentiate normal from abnormal myocardial structure. We tested this hypothesis with quantitative texture measures to study the regional, spatial distribution of echo amplitudes in 2D echocardiograms performed before and immediately after blunt left chest trauma was induced in six anesthetized dogs. After trauma the contused region of myocardium appeared brighter and exhibited an altered myocardial texture. By use of a set of quantitative texture measures, we found no significant differences in pretrauma images when normal regions were compared with regions to be contused. Also, we found no difference when we compared the normal regions in each animal in pretrauma vs posttrauma images. Twelve measures, however, differentiated normal from contused regions within the posttrauma images (p values ranged from .0057 to .0001 by multivariate analysis of variance). These texture measures were capable of differentiating normal from abnormal tissue only when texture along the azimuthal (lateral) direction was calculated. We conclude that regions of myocardial contusion exhibit visibly altered local echo-amplitude patterns (altered image texture) and that these image texture alterations may be quantified with digital image analysis techniques. These findings suggest that quantitative texture calculations may be a useful approach to ultrasound tissue characterization.

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STANDARD clinical echocardiography, M mode and two-dimensional (2D), consists of the depiction of large, smooth (specular) reflectors such as endocardium and epicardium. The clinical use of lower amplitude backscatter returning from the myocardium has remained relatively unexplored. However, there has been growing interest in the study of backscatter and other acoustic properties of normal and abnormal tissue, referred to as "ultrasound tissue characterization."

This area of investigation is based on the assumption that abnormalities in the microscopic structure of a soft tissue region will influence the acoustic characteristics of that tissue. Various approaches that have been used in ultrasound tissue characterization studies include attempts at direct visualization of regions with abnormal acoustic properties, measurement of acoustic parameters of interest, and analysis of displayed features of two-dimensional images or patterns present in the ultrasound signal with statistical or other digital computer image analysis techniques. The analysis of 2D echocardiographic image texture is an example of the latter approach. Unusual regional or global myocardial image texture has occasionally been visualized in clinical 2D echocardiograms in disorders such as hypertrophic cardiomyopathy. These observations have been qualitative and sporadic. Much has been written about the use of quantitative texture measures in the evaluation of a wide range of pictorial data. Although some early attempts have been made to use classic texture analysis for the evaluation of A mode ultrasonograms, few
data are available on the use of these techniques to evaluate 2D echocardiograms.

In the present study we defined 2D echocardiographic image texture as the regional two-dimensional spatial distribution of echo intensity (amplitude) information. In previous studies we have evaluated tissue acoustic properties by assessing echo amplitude (gray level) distributions in regions of digitized 2D echocardiograms.20 The two-dimensional spatial pattern of gray levels, however, may contain more information than is apparent in the overall distribution of gray levels (figure 1). We postulated that the analysis of regional image texture in 2D echocardiograms would be an accurate method to differentiate normal from abnormal myocardial structure. We tested this hypothesis with classic texture measures to study the regional texture in standard 2D echocardiograms performed before and after experimental myocardial contusion.

We chose myocardial contusion as a model for our experiments because of the frequently recognized difficulty in making this diagnosis.21 Contusion of the myocardium may produce no significant symptoms and is often overlooked because of associated chest wall injury.24 Many of the usual diagnostic tests for acute ischemic necrosis are less specific in this setting and a new approach to diagnosis might be of considerable use.23

Methods

Experimental preparation. Six adult mongrel dogs were studied in this experiment. The dogs were anesthetized with pentobarbital (500 mg iv), followed by chloralose (1 to 1.5 gm iv). Catheters were placed in the femoral vein (for administration of medications) and in the femoral artery and left ventricle (for pressure monitoring). The surface electrocardiogram was also monitored.

Technique of myocardial contusion. After induction of deep anesthesia, blunt chest trauma was produced with the method described by Anderson and Doty.25 A captive bolt pistol (Aecles and Shelvoke, Ltd., England) with a specially machined semielliptical 2 in steel disc attached to the end of a piston was used. The disc was held firmly against the left parasternal area, a .22 caliber cartridge was fired, the bolt was propelled forward, and injury resulted from transfer of kinetic energy through the intact chest wall to the myocardium. Between one and three contusions were administered to each animal to produce noticeable changes in wall motion and thickening of the anterolateral myocardium on 2D echocardiograms taken immediately after the contusion was induced.

Echocardiographic studies. We obtained 2D echocardiograms with a standard electronic sector scanner operating at 2.4 MHz (Toshiba SSH-10A Sonolayergraph). The echocardiograms were performed with the animals in a right lateral decubital position on a specially prepared table.26 The echocardiographic transducer was placed through a cutout in the table onto the right chest wall of the animal near the point of maximal cardiac impulse. Standard short-axis echocardiograms were obtained at mitral valve, chordal, and papillary muscle levels and were recorded immediately before and approximately 30 min after the administration of blunt chest trauma. Time-gain compensation and overall-gain settings were adjusted to produce echocardiographic images in which the average brightness of all tissue regions appeared approximately the same. Scanner receiver settings, including dynamic range, echo enhance, overall gain, and time-gain compensation controls, were kept constant between the two examinations. Video monitor brightness and contrast settings were also kept constant. Echocardiograms were recorded on ¾ inch video tape. In addition, our scanner had the capability to digitize and store a freeze-frame image and to display it on the primary cathode ray tube monitor. With this freeze-frame device we digitized, stored, and displayed frames at end-systole (defined as the smallest apparent cavity area) and photographed them from the cathode ray tube monitor.

Experimental protocol. After the control echocardiographic recordings, blunt chest trauma was administered as described above. Immediately after trauma, ventricular arrhythmias and hypotension frequently occurred. These were treated as necessary with electric defibrillation, lidocaine, saline, and epinephrine. The animals were stabilized, and approximately 30 min after trauma another echocardiogram was obtained. The short-axis views were obtained at approximately the same level before and after trauma using internal landmarks (e.g., the configuration of the papillary muscles). After the posttrauma echocardiogram the animals were killed with intravenous potassium chloride and the hearts were removed. The hearts were examined grossly and standard histologic sections of normal and contused tissue were prepared after formaldehyde preservation and hematoxylin-eosin staining.27

Image processing and analysis. The digital freeze-frame images of the left ventricle in short-axis orientation were photographed with Polaroid 665 positive/negative film with a camera f-stop at 4.5 and an exposure duration of 5 sec. Photographic negatives were cleared with a sodium sulfite solution. The photographic negatives were placed on a light table and digitized with a video camera (Hamamatsu C-1000) interfaced to a PDP 11/34 computer and to a Ramtek image display system. The data were digitized into a 256 x 256 pixel matrix with eight-bit gray-level quantization. Theoretically this permits the echocardiographic intensity to be quantized to 256 levels. However, the effective number of gray levels that can be distinguished is less and depends on the dynamic range of the primary display moni-
tor, film grain and emulsion characteristics, film processing, and video camera signal-to-noise ratio. Pretrauma and posttrauma images were always digitized sequentially under identical conditions of ambient illumination.

The trauma was administered to the left chest of the animal; therefore, the expected area of contusion was the anterolateral left ventricular wall. For this reason, regions of interest in the digitized images were chosen in the anterolateral wall and in the opposite, normal, posterior ventricular septum. Care was taken to avoid the inclusion of the specular reflections from the endocardium and epicardium in the regions of interest. Further, the two regions of interest in each image were placed at approximately the same distance from the transducer. This was done because of the previous demonstration of significant variations in echo-amplitude data as a function of distance from the transducer and of position in the echocardiographic field of view. Verification of the areas presumed to be contused and normal was obtained at the end of each experiment by comparison with the pathologic specimens.

Before analysis of each region with quantitative texture measures, each image was subjected to a smoothing procedure with a five-pixel weighted average filter. The purpose of this filter was to remove the extraneous texture in the image caused by the radial sector scan lines. We chose this technique after several methods of smoothing and several "window" sizes were tested. We found that this filter effectively removed much of the sector scan line appearance without noticeably altering the apparent myocardial image texture.

Texture analysis algorithms. The image data were analyzed with measures related to the intensity and distribution of echo amplitude (gray levels) within each region. These variables may be divided into four groups: (1) gray level histogram statistics, (2) edge count (3) gray level run-length statistics, and (4) gray level difference statistics. These techniques are summarized briefly here and specific algorithms are given in the appendix. *

Gray level histogram statistics. The overall distribution of echo amplitudes within each region of interest was assessed by an evaluation of the gray level frequency histogram as previously described. The mean gray level was the variable examined in this study and was calculated as the average of the gray level values of all pixels within each region of interest. The average gray level of the cavity was subtracted from the average gray level of each tissue region in the same image to correct for variations in echocardiographic, photographic, and digitization technique between images.

Edge count. A two-dimensional, gradient-based edge operator (Sobel) was used to identify edge points within each region of interest. This algorithm determined the presence of edges within each region of interest by calculating the difference in gray level across each pixel in the region in both vertical and horizontal directions (see Appendix, footnote). If the difference in gray level values exceeded an operator-identified threshold, the pixel was said to represent an edge. The threshold was determined in each case from an examination of the gray level histogram of the region of interest and the same threshold was used for both normal and contused regions within a given image. After the application of the edge operator, a thinning algorithm was implemented to remove extraneous edge points. After the thinning operation the number of the edge points within each region of interest was counted. The purpose of the edge-count variable was to identify the heterogeneity of gray levels within the region of interest. That is, a region of homogeneous gray level value would display few edge points and a heterogeneous region of interest would display many edge points.

Gray level run-length statistics. A gray level run is defined as a set of consecutive, collinear pixels having the same gray level value or gray level values within a given range. The length of a run is the number of pixels traversed before a change in gray level value. Four gray level run-length variables were calculated (see Appendix, footnote). (1) long run emphasis, (2) short run emphasis, (3) run-length nonuniformity, and (4) gray level nonuniformity. Conceptually, the gray level run-length statistics are measures of the heterogeneity of gray levels and of the relative size of individual echocardiographic reflections within the area of interest. A region with relatively large individual echocardiographic reflections will yield long run-length values, whereas a region containing small individual echocardiographic reflections will yield short run-length values. The nonuniformity statistics calculate the homogeneity or heterogeneity of the size of echocardiographic reflectors within the region of interest.

Gray level difference statistics. The gray level difference statistics are also measures of the heterogeneity of the distribution of echocardiographic reflections within a region of interest. The gray level difference statistics are (1) contrast, (2) angular second moment, (3) entropy, and (4) mean. These statistics are calculated by measuring the difference in gray level value between pixels separated by various distances in various directions (see Appendix, footnote). We calculated the difference in gray level values between picture points separated by one, two, four, and eight pixels in both horizontal and vertical directions.

The gray level run-length and gray level difference statistics were calculated along both horizontal and vertical directions. This was done because previously demonstrated variability in texture data obtained from ultrasound images was dependent on the direction of calculation of the texture parameter. The data analysis. With multivariate analysis of variance, three comparisons were calculated from our data: (1) texture calculations from the anterolateral wall (contusion region) were compared with those from the posterior ventricular septum (normal region) in the images obtained before myocardial contusion (control images); (2) texture calculations from normal and contused regions were compared in the images obtained after contusion (posttrauma images); and (3) texture calculations from the posterior ventricular septum (normal region) were compared between the control and posttrauma images. Because, in the last case, these regions presumably were not contused, this comparison served as a control for variability in echocardiographic, photographic, and digitization techniques between the first and second 2D echocardiographic studies. Because of the large number of variables calculated, the required level for statistical significance was $p < .008$ with the Bonferroni multiple comparison method. 33

Results

All six animals survived the blunt chest trauma and were sufficiently stable hemodynamically to undergo follow-up echocardiographic studies at 30 min after trauma.

Pathologic examinations. In each of the excised hearts, gross pathologic examination revealed contusion and hemorrhage that involved chiefly the anterolateral left
ventricular wall. Microscopic examination revealed focal hemorrhage with hematoma formation, as well as myofibrillar fragmentation. The posterior region of the ventricular septum, which appeared normal on the echocardiograms, was confirmed as normal by the pathologic examination.

**Qualitative echocardiographic observations.** The region of contusion was noticeably brighter on examination of the posttrauma echocardiographic studies (figure 2). In addition, the pattern of the echocardiographic reflections in the contused regions appeared altered, with larger individual echocardiographic reflections and coalescence of individual echocardiographic reflections.

**Texture calculations.** No significant differences in texture calculations were found when we compared normal regions with regions to be contused in pretrauma images, nor when we compared the normal regions in each animal in pretrauma vs posttrauma images. Twelve texture variables did, however, differentiate normal from contused regions in the posttrauma images, as shown in table 1 (p values range from .0057 to .0001).

As suggested by the brighter appearance of the contused regions, the average gray level was increased compared with the normal myocardium of the ventricular septum (figure 3). In addition, gray level run-length long run emphasis, calculated along the horizontal direction, was significantly larger in the contused region compared with the normal myocardium (figure 3), which suggests the presence of larger individual echocardiographic reflections. Finally, all four gray level difference statistics were significantly altered in the contused region for separations of one and two pixels in the horizontal direction. Two of the gray level difference statistics (angular second moment and entropy) were also significantly altered along the horizontal direction for a separation of four pixels.

When texture measures along the vertical direction were calculated, none of the directional variables (i.e., gray level run-length or gray level difference statistics) was able to successfully differentiate contused from normal myocardium. Although there was a trend (p < .02) for an alteration in edge count after contusion, the difference was not statistically significant.

**Discussion**

In the present study we found that regions of myocardial contusion exhibited visibly altered local echomplitude (gray level) patterns (i.e., altered image texture) on standard 2D echocardiograms. Further, we found that these image texture alterations could be quantified with digital image analysis techniques. These findings suggest that quantitative texture calculations may be a useful approach to ultrasound tissue characterization — an analysis that in some instances may be applied to standard 2D echocardiographic images.

**Previous observations on 2D echocardiographic texture.** Previous workers have noted altered regional 2D echo-

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**FIGURE 2.** Short-axis echocardiographic frames at papillary muscle level before (left) and after (right) blunt left chest trauma. The overall brightness of the contused region (arrows) is increased and the pattern of echoes (texture) is different than that in the control frame. In this case, the region of contusion, and of altered texture, included the anterolateral and posterolateral walls (arrows).
TABLE 1
Texture measures that distinguished normal from contused myocardium (mean ± SD)

<table>
<thead>
<tr>
<th>Texture measures</th>
<th>Control</th>
<th>Posttrauma</th>
<th>p value</th>
<th>p value*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Septum</td>
<td>Anterolateral LV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean gray level</td>
<td>88±12</td>
<td>80±20</td>
<td>NS</td>
<td></td>
</tr>
<tr>
<td>Run length LRE-0°</td>
<td>5.2±1.2</td>
<td>5.9±1.2</td>
<td>NS</td>
<td></td>
</tr>
<tr>
<td>Gray level DIFF-0° Δ = 1</td>
<td>215±75</td>
<td>170±60</td>
<td>NS</td>
<td></td>
</tr>
<tr>
<td>Contrast</td>
<td>0.044±0.010</td>
<td>0.050±0.010</td>
<td>NS</td>
<td></td>
</tr>
<tr>
<td>ASM</td>
<td>3.3±0.20</td>
<td>3.2±0.19</td>
<td>NS</td>
<td></td>
</tr>
<tr>
<td>Entropy</td>
<td>0.046±0.009</td>
<td>0.041±0.007</td>
<td>NS</td>
<td></td>
</tr>
<tr>
<td>Δ = 2</td>
<td>659±222</td>
<td>527±188</td>
<td>NS</td>
<td></td>
</tr>
<tr>
<td>Contrast</td>
<td>0.025±0.005</td>
<td>0.028±0.006</td>
<td>NS</td>
<td></td>
</tr>
<tr>
<td>ASM</td>
<td>3.9±0.18</td>
<td>3.8±0.18</td>
<td>NS</td>
<td></td>
</tr>
<tr>
<td>Entropy</td>
<td>0.079±0.015</td>
<td>0.071±0.014</td>
<td>NS</td>
<td></td>
</tr>
<tr>
<td>Δ = 4</td>
<td>0.016±0.002</td>
<td>0.018±0.003</td>
<td>NS</td>
<td></td>
</tr>
<tr>
<td>ASM</td>
<td>4.3±0.11</td>
<td>4.2±0.12</td>
<td>NS</td>
<td></td>
</tr>
<tr>
<td>Entropy</td>
<td>0.018±0.004</td>
<td>0.024±0.007</td>
<td>NS</td>
<td></td>
</tr>
</tbody>
</table>

LV = left ventricle; LRE-0° = long run emphasis computed in the horizontal direction; DIFF-0° = gray level differences computed in the horizontal direction; Δ = distance between sampling points (pixels); NS = not significant.

* A value of p < .008 is required for statistical significance.

cardiographic gray level patterns in a variety of disorders. Rasmussen et al., demonstrated that scar tissue appeared brighter than normal myocardium on M mode echocardiograms. Martin et al., reported unusual 2D echocardiographic image characteristics in the ventricular septum of patients with hypertrophic cardiomyopathy. Similar observations have been made on images of patients with amyloid heart disease. Bhandari and Nanda have examined myocardial echocardiographic patterns in several cardiac abnormalities both in vitro and in vivo and have correlated these patterns with histopathologic findings.

These previous observations support the concept that image texture contains useful information that is available in standard, clinical echocardiograms. However, prior experience and descriptions have been qualitative; calculation of 2D echocardiographic image features related to texture has not previously been accomplished.

Mechanisms of echocardiographic image texture. Image texture may be defined as the two-dimensional spatial distribution of an attribute of interest in a picture — in the case of 2D echocardiography the attribute is echo amplitude or gray level. The bright echocardiographic images seen from the epicardium and endocardium represent specular reflections from these smooth interfaces, which are large compared with the wave length of diagnostic ultrasound. In contrast, the echocardiographic patterns from myocardium are lower amplitude reflections arising from many small interfaces (small compared with the wavelength of the echocardiographic signal). These multiple reflections produce complex interference patterns that have been referred to as acoustic "speckle." The echocardiographic image texture we studied, and that described by previous workers, is in large part acoustic speckle. The precise relationship between the acoustic speckle pattern and the responsible underlying anatomic structures is extremely complicated and has not been well characterized. Further, the specific appearance of the speckle pattern in a 2D echocardiographic image is substantially dependent on the specific ultrasound scanning instrument used to generate the image. Nonetheless, this speckle pattern seems to be altered in various conditions that affect the microstructure of the myocardium. It was our goal to attempt to quantify alterations in myocardial texture patterns caused by myocardial con-
FIGURE 3. The results of three representative texture calculations are shown for normal and contused regions in the posttrauma images; values are means (± so). The mean gray level and selected run-length and gray level difference statistics were significantly altered in regions of myocardial contusion; Asterisk, p = .0001; dagger, p = .0018; filled circle, p = .0015; LRE-0° = long run emphasis calculated along 0° (in azimuth); (Δ = 2) = gray level difference contrast calculated for a pixel separation of two.

myocardium. The alterations in the texture calculations were consistent with larger individual echocardiographic reflections and a more homogeneous distribution of echo amplitude in the contused regions. These differences were presumably caused by the presence of areas of hemorrhage (including hematoma) and myofibrillar fragmentation after trauma. The interfaces between the areas of hemorrhage and normal tissue also were presumably the cause of the increased average gray level of contused regions.

Of interest was the observation that the texture calculations were most useful when carried out in the direction perpendicular to the main ultrasound beam. This may relate to the fact that different factors affect image texture in range vs azimuth in B mode scans, as described by Flax et al.28 For example, the two-point resolution of standard 2D echocardiographic systems is different in range (axial) than in azimuth (lateral), and the azimuthal resolution varies in different portions of the sector image.28 The latter observation suggests that image characteristics, and therefore texture calculations, will vary as a function of the position of the region of interest within the sector field-of-view. Flax et al.28 predicted this phenomenon in B mode scans, and we have previously shown that texture calculations do vary as a function of range and azimuth in 2D echocardiographic images, even when a uniform scattering phantom is imaged.29 The causes of this variation in speckle pattern with position of the region of interest have not been fully studied or elucidated. Therefore, we limited our analysis in this study to two regions of interest that were carefully placed in each image at approximately the same distance from the transducer.

Future directions and implications. Previous qualitative observations and our data suggest that quantitative texture calculations may prove effective indicators of abnormal vs normal myocardium. Abnormalities that are potentially detectable by texture analysis include myocardial necrosis, fibrosis, and infiltrative cardiomyopathies, all of which disrupt normal myocardial architecture and may therefore be expected to alter image texture patterns. However, our model of experimental myocardial contusion produced severe, gross injury to the myocardium, and the use of quantitative texture analysis in detecting more subtle microscopic alterations in tissue structure remains to be explored.

To use these calculations in a more general manner, further investigations will need to address two areas. More information is needed concerning the physical mechanisms of the interactions between ultrasound and myocardium. Specifically, the relationship between the detected (video) ultrasound signal, the speckle pattern seen in clinical 2D echocardiographic images, and the underlying arrangement of ultrasound scatterers in myocardium needs to be explored more fully. Intimately related to these considerations is the need to understand more completely the effect of instrument settings, transducer geometry, focusing methods, and methods of gain compensation on displayed image texture. In this way we may gain an improved understanding of which features of displayed echocardiographic image texture are related to tissue structure and which features are related more to the specific instrument employed.28

At present, quantitative echocardiographic texture analysis must be considered to be an investigatory technique. However, the growing number of observations concerning echocardiographic image texture and recent research aimed at improved understanding of acoustic speckle and at the reduction of speckle26, 37 suggest that texture analysis may be of increasing use in ultrasound myocardial tissue analysis.
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