An Echocardiographic Technique for Quantifying and Displaying the Extent of Regional Left Ventricular Dyssynergy

DAVID E. GUYER, MD, FACC, RODNEY A. FOALE, MBBS, LINDA D. GILLAM, MD, FACC, GERARD T. WILKINS, MB, CHB, J. LUIS GUERRERO, ARTHUR E. WEYMAN, MD, FACC

Boston, Massachusetts

A convenient noninvasive method of mapping the left ventricular endocardial surface has been developed that can be used to display regional dysfunction and calculate the total area of abnormal endocardial excursion from data obtained in two orthogonal apical and three or more short-axis cross-sectional echocardiographic images. Visually identified regions of abnormal systolic function are plotted on end-diastolic, planar endocardial surface maps, and the extent of dysfunction can be expressed either as an absolute area or as a fraction of the total endocardial surface area involved. The extent of the left ventricular surface moving abnormally, calculated with this echocardiographic mapping technique, was compared with two histochemical measures of infarct size in a series of 11 closed chest dogs with acute circumflex coronary artery occlusions. Overall extent of abnormally moving left ventricular wall correlated closely with both the fraction of the endocardial area overlying infarct \( r = 0.92, p \leq 0.001 \) and the fraction of the myocardial volume infarcted \( r = 0.86, p \leq 0.001 \). This suggests that the echocardiographic mapping technique can be used to accurately quantify the global extent of abnormal systolic function in the presence of regional wall motion abnormalities.

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Methods

Animal preparation, infarct protocol and histochemical staining. Eleven adult mongrel dogs weighing between 15 and 25 kg were prepared for closed chest echocardiographic examination by partial rib resection and creation of a pericardial cradle. This technique is described in detail elsewhere (5). The circumflex coronary artery was prepared for occlusion in all of these animals.

On the day of coronary ligation, each animal was anesthetized with intravenous sodium pentobarbital (30 mg/kg bodyweight), intubated and ventilated using oxygen-supplemented air and 5 cm water positive end-expiratory pres-
sure. A baseline echocardiographic study was obtained to ensure normal wall motion before coronary ligation, and then the left circumflex coronary artery was occluded by tightening an occluder. Six hours later, a second echocardiographic study was obtained. The animal was then killed using an intravenous anesthetic overdose and the heart was excised. Histochemical staining was obtained using 2,3,5-triphenyltetrazolium chloride (TTC) (5). The left ventricular cavity of each heart was then packed with cotton gauze, frozen and sliced transversely into sections that were approximately 1 cm in width (Fig. 1A). The outlines of each slice and its TTC-defined region of infarction were traced onto a clear plastic sheet, and a color photograph of each slice was also taken as a permanent record. Myocardium that did not stain with TTC was assumed to be infarcted (6).

**Echocardiographic data collection.** The echocardiographic studies were obtained with an ATL Mark III mechanical sector scanner using either a 3.5 or a 5 MHz transducer (Advanced Technology Laboratories), and were recorded on 0.5 inch (1.27 cm) VHS magnetic tape with a Panasonic NV-8200 video tape recorder (Matsushita Electric Industrial Co., Ltd.). All studies were recorded with Panasonic equipment (Advanced Technology Laboratories), and were transferred to computer storage for analysis using a video digitizing system (Easyview II, Microsonics, Inc.).

Each dog was reviewed and optimal frames for measurements were identified. These frames were then transferred to a videodisc. The desired dimensions were then measured with a video digitizing system (Easyview II, Microsonics, Inc.). Each dimension was measured three times in separate frames, and the measurements were averaged. End-diastole was defined by the peak of the R wave of the electrocardiographic monitor lead. The required end-diastolic dimensions (4) were

Figure 1. A, Schematic diagram showing how the preserved stained and frozen left ventricle of experimental animals was sliced transversely for quantification of histochemical infarct sizes. B, Methods of determining the histochemical extent of infarction by calculating the percent fraction of the endocardial surface overlying histochemical evidence of infarction and the percent fraction of the myocardial volume infarcted. $\Sigma = \text{summations performed over all slices. Endocardial area: Area affected (EAA)} = \Sigma S_1 \times Th_1$; total area (TEA) $= \Sigma C_1 \times Th_1$; % area affected $= 100 \times (EAA/TEA)$. Myocardial volume: Volume affected (MVA) $= \Sigma A_1 \times Th_1$; total volume (TMV) $= \Sigma A_1 \times Th_1$; % volume affected $= 100 \times (MVA/TMV)$.

The apical four chamber plane was located by placing the echocardiographic transducer over the left ventricular apex and directing the central ray of the beam toward the crux of the heart. The beam was then adjusted to maximize the excursion of both the mitral and tricuspid valve leaflets. Some difficulty was occasionally encountered in obtaining optimal apical four chamber views with this canine preparation because of the subxiphoid location of the apex. However, all images were adequate for measurements of ventricular dimensions and for the delineation of regions with abnormal wall motion.

The two chamber imaging plane of the left ventricle was routinely recorded from a parasternal window in this animal preparation. The transducer was placed above the anterior left ventricular wall with the scan plane directed in an apex to base orientation. The left ventricular apex was readily seen from this position. This view provided the same echocardiographic information as the apical two chamber imaging plane, but it improved resolution of the endocardial-blood pool interface with the axial resolution of the imaging system.

**Short-axis images were also recorded from a left parasternal transducer position.** These were obtained at mitral valve, midpapillary muscle and apical levels. In each case, the images were optimized by minimizing any obliquity in the normally circular short axis of the left ventricle at end-diastole.

**Echocardiographic data analysis.** The echocardiographic mapping technique uses quantitative data from the standard echocardiographic imaging planes to derive maps of the three-dimensional endocardial surface. That surface is considered to be a thin membrane which, when quadrisectioned by apex to base cuts oriented like the apical echocardiographic imaging planes, is divided into four sections and can be laid flat with a minimum of distortion to form a map. This is somewhat analogous to the cartographer’s procedure for making a planar map of the terrestrial globe. The mapping technique is described in detail in an accompanying communication (4).

**Construction of endocardial maps from echocardiographic measurements.** The echocardiographic study of each dog was reviewed and optimal frames for measurements were identified. These frames were then transferred to a videodisc. The desired dimensions were then measured with a video digitizing system (Easyview II, Microsonics, Inc.). Each dimension was measured three times in separate frames, and the measurements were averaged. End-diastole was defined by the peak of the R wave of the electrocardiographic monitor lead. The required end-diastolic dimensions (4) were
then entered into the iterative mapping algorithm to produce endocardial surface maps.

Mapping regions of dyssnergy. Areas of abnormal endocardial excursion were defined visually in each echocardiographic imaging plane, and the lengths of abnormally moving segments were then quantified by superimposing end-systolic and end-diastolic frames. The positions of abnormal regions within an imaging plane were determined by reference to internal cardiac landmarks: the distances along the endocardial surface from the mitral valve plane in the apical images, and the distance from mitral commissural axis or papillary muscles in the short-axis planes. Then, the margins of dyssynergic segments were marked at their appropriate locations on the map. These end points were then connected by straight line segments, and the enclosed area was taken to represent the region of abnormal wall motion. The percent of the endocardial surface area that moved abnormally was calculated as the ratio:

\[ \frac{100 \times \text{Abnormally moving area}}{\text{Total endocardial area}} \]

Histochemical infarct size. The extent of infarction in each heart was calculated from histochemical staining after the animal was killed, as described earlier. The following measures of infarct extent were used:

1) The fraction of the endocardial surface area overlying infarcted muscle was calculated as shown in Figure 1B. The smoothed endocardial area of each heart slice was determined by multiplying slice width by endocardial circumference. Slice width was measured directly, and the circumference was determined by outlining the endocardial border of the slice tracing on a digitizing pad. The endocardial area overlying infarcted muscle was computed as the product of slice width and endocardial segment length overlying infarction in that slice. These areas were summed for all slices from a given ventricle to calculate both the total endocardial area and the "endocardial area affected." The percent fraction of the endocardial area overlying infarction was simply calculated from the ratio of these two areas.

2) The volume of infarcted myocardium was calculated with a Simpson's rule technique, multiplying the infarcted area on the basal surface of each slice by the slice width and adding the resulting infarct volumes of all slices from each heart. Total myocardial volume was computed analogously. The percent myocardial volume affected was calculated from the ratio of infarct volume to total myocardial volume (Fig. 1B).

Statistical techniques. The map-derived fraction of the endocardial surface moving abnormally was compared with the two histochemical indices of infarct size using least squares linear regression. Correlation coefficients, standard errors of the estimate and levels of significance for the two comparisons were calculated.

To estimate interobserver variability, the linear dimensions and extent of infarction were measured by two separate observers in 5 of the 11 dogs. Each observer independently chose the echocardiographic frames in which to make measurements. Overall agreement was within 5% for linear measurements, as previously reported from this laboratory (5).

Figure 2. Representative endocardial map of one dog (M-02) which had an inferior myocardial infarction after experimental ligation of the left circumflex coronary artery. The dimensions shown on the figure were measured at end-diastole. The stippled area represents the region of echocardiographically determined abnormal wall motion. \( C_{MV} \) = short-axis circumference at the mitral valve level; \( C_{PM} \) = circumference at midpapillary muscle level; \( C_{AP} \) = circumference at midpapillary muscle level; \( L_{ax} \) = central long-axis dimension of the ventricle. Not shown in this figure is the endocardial apex to base segment length, which was 8.2 cm. Endocardial area: Area affected = 43.2 cm²; total area = 101.9 cm²; %area affected = 100 \times (43.2/101.9) = 42.4%.
inferior septum, inferoposterior wall and the entire apex of the ventricle.

Correlation with histochemical evidence of infarction. Nine of the 11 dogs undergoing circumflex artery ligation developed histochemical evidence of myocardial infarction. In these nine dogs, there was echocardiographic akinesia or dyskinesia in the inferior and posterior segments of all, and inferoseptal and posterolateral akinesia or hypokinesia in six. In addition, six of the nine animals with infarction had echocardiographic evidence of apical akinesia or dyskinesia. Two dogs did not develop histochemical evidence of infarction despite coronary snare occlusions. No wall motion abnormality was seen on the echocardiographic study of either of these two animals.

Estimate of the fraction of the endocardial surface moving abnormally calculated from the echocardiographic maps ranged from approximately 25 to 42% in the nine dogs with histochemical evidence of infarction. In the same nine dogs, the ranges of the histochemical indexes of infarct extent were 20 to 50% of the endocardial surface area, and 9 to 33% of the myocardial volume.

Correlation of abnormal wall motion with infarct size. Graphs correlating the fraction of the endocardial surface with abnormal wall motion, determined from the maps, with the histochemical indexes of infarct extent are shown in Figures 3 and 4. The echocardiographic extent of abnormal wall motion and the fraction of the endocardial surface area overlying infarcted myocardium have a correlation coefficient of $r = 0.91$ (Fig. 3). Map-derived estimates of extent of abnormal endocardial motion overestimated the volume fraction of muscle that was infarcted, but the overall correlation coefficient was 0.87 (Fig. 4).

Discussion

Previous studies. The extent of left ventricular dysfunction after acute ischemia or infarction has been shown in angiographic studies to be a fundamental determinant of subsequent left ventricular performance, and therefore has major diagnostic implications. One index that has been used to estimate the overall extent of dyssynergy is the fraction of the left ventricular endocardial surface displaying abnormal wall motion. Klein et al. (8) analyzed single plane left ventriculograms (in the right anterior oblique projection) and concluded that when more than 20% of the endocardial surface becomes aneurysmal, end-diastolic pressures and volumes rise. Their analyses further revealed that when more than 20 to 25% of the left ventricular inner surface is akinetic or dyskinetic, chamber dilation is necessary to maintain stroke volume, and so ejection fraction falls. Kitamura et al. (9) noted that left ventricular end-diastolic pressure and volumes increased with increasing fractions of the endocardial surface moving abnormally in patients with coronary artery disease. In a later study, Kitamura et al. (10) determined that fractional areas of dyssynergy between 20 and 30% are required for left ventricular failure to become clinically manifest. Swan et al. (2) developed a theoretical model that related elevations in left ventricular diastolic pressure and volumes and decreases in ejection fraction to both the diastolic compliance characteristics of noncontracting portions of the ventricle and the fraction of the endocardial surface area not contributing to ejection.

These and other theoretical-empirical models relating endocardial area of dysfunction to global left ventricular performance involve major geometric assumptions. In addition, the inability of any blood pool imaging technique to examine
wall motion in portions of the ventricle that are not border-forming limits the overall accuracy of such methods when used to quantify extent of dysfunction.

**Echocardiographic approaches to quantify wall motion abnormalities.** Although the utility of cross-sectional echocardiography in detecting wall motion abnormalities that result from coronary artery disease has been demonstrated in a number of studies (11–14), echocardiographic quantification of the global extent of dyssynergy has proved more difficult. To date, three general approaches have been used: the segmental approach, the geometric figure technique and the summation of function in multiple parallel short-axis planes.

To use the segmental method of evaluating function, the left ventricle is divided into a number of approximately equally sized segments, and each segment is assigned a score on the basis of its visually defined function. The functional scores of all of the ventricular segments are then added to derive the overall score, which is an index of left ventricular performance. Although several studies have demonstrated good correlations between ventricular scores and hemodynamic condition (11), short-term mortality (12,13) and radionuclide estimates of infarct size (14), the segmental approach is the least precise method of localizing an infarct and estimating its area. For example, if a ventricle is divided into 10 segments the maximal spatial resolution of that segmental system is in 10% increments, and the score assigned to each of the 10 regions must reflect an average function within that large segment.

*Representation of the endocardial surface as a single geometric figure or as a combination of figures has been used to estimate endocardial area (15,16).* The area of abnormal wall motion is then calculated as a subsegment of the overall endocardial area. In one study (15), the endocardial surface was represented as a truncated cone, and the extent of abnormal wall motion correlated inversely with short-term survival. However, this model was never validated in an experimental setting. Furthermore, the geometric figure method is not easily applied to deformed ventricles.

The overall extent of regional dysfunction can also be calculated from multiple short-axis echocardiographic images using a Simpson’s rule technique to add the areas of dysfunction from each plane (17). This type of approach is potentially the most accurate of the three discussed so far, but its usefulness in the evaluation of clinical infarction is limited by the restrictions that human anatomy place on acquiring an adequate number of parallel short-axis images.

**The echocardiographic mapping technique.** The need remains for an accurate, reproducible, noninvasive method for quantifying the extent of abnormal left ventricular wall motion. The echocardiographic technique for mapping the left ventricular endocardial surface, which is described in detail in an accompanying report (4), should provide a suitable basis for such a quantitative analysis of dyssynergy making use of data that are available in standard cross-sectional echocardiographic images.

The present study shows how the mapping concept can be extended to the quantification of areas with abnormal wall motion. Visually identified regions of dyssynergy are measured in three short-axis and two mutually perpendicular apical imaging planes, and the positions of these abnormal regions are then localized using internal cardiac landmarks. The end points of regions of dysfunction are then plotted in their relative positions on the corresponding end-diastolic endocardial map, and the area of abnormal wall motion is delineated and measured by connecting the end points with straight line segments.

Comparison of the area of abnormal wall motion, expressed as a fraction of the total endocardial area, with two histochemical indices of infarct extent revealed relatively good correlations in this series of acute canine myocardial infarction. When the volume fraction of myocardium infarcted was the standard of comparison, the area of abnormal wall motion uniformly overestimated the histochemical extent (Fig. 4). This overestimation of infarct volume is in keeping with available data from angiographic (18) and echocardiographic (19) studies in humans, and both M-mode (20) and cross-sectional echocardiographic (17) studies in dogs.

**Correlation of wall motion and infarct size.** When we compared a second histochemical index of infarct size, the fraction of the endocardial surface overlying infarcted myocardium, with the map-determined extent of dyssynergy, there was a more variable relation between wall motion and disease. This variability is likewise in keeping with previous observations. In some experimental settings wall motion has been found to overestimate infarction, this discrepancy being attributed to dysfunction of ischemic but noninfarcted regions and to mechanical tethering of areas adjacent to infarct (21). However, other data indicate that localized abnormalities of wall motion may, on occasion, underestimate the area of infarction. Stinson and Billingham (22), compared wall motion in the anteroapical segment, assessed by contrast ventriculography, with the histologic results of transmural needle biopsy of that same wall. They reported a 23% incidence rate of normal wall motion in the presence of fibrosis in patients who did not have a Q wave infarction. Weiss et al. (19) found normal echocardiographic wall motion in 21% of regions with underlying subendocardial infarction (defined as involving less than 33% of the wall thickness), although wall motion abnormalities more frequently exceeded the pathologic evidence of infarction. Meltzer et al. (16) noted that endocardial excursion determined from cross-sectional echocardiograms could underestimate the extent of technetium-99m stannous pyrophosphate uptake in an experimental canine preparation. Although these studies are limited in that they examine correlations between wall motion and infarct size only in single tomo-
graphic segments or subsegments of the ventricle, the variables noted in them are consistent with our data for the overall area of abnormal systolic function.

Implications. The purpose of these comparisons was to confirm that the extent of dysfunction determined with the mapping technique corresponds to underlying histochemical evidence of infarction. In animals and humans, infarcts resulting from similar coronary occlusions can have considerable spatial and transmural heterogeneity. Likewise, left ventricular systolic function is affected by the interaction of multiple factors, including ventricular loading conditions and sympathetic tone, in addition to either necrosis or fibrosis. Therefore, it was recognized that the variables in the functional expression of infarcts and their histochemical extents would make any correlation of these two variables imperfect. Because it is function rather than histology that determines the hemodynamic effects of an infarct on the whole organism, it seems reasonable to define and serially evaluate the extent of regional dysfunction as an independent variable, expecting a general, albeit imperfect correlation with histologic infarct size.

To identify regions of abnormal endocardial excursion, the echocardiographic study of each dog was visually analyzed in the five standard imaging planes used to define the endocardial maps. The linear extent of abnormal wall motion in each of these planes was measured and subsequently plotted on the resulting map. This technique of visually identifying and quantifying dyssynergy has been previously validated for short-axis tomographic planes (19), and no automated system for analyzing short-axis images has been shown to be more accurate. Furthermore, the visual identification of abnormal segments is the only method available at present for use with apical echocardiographic images. When more sophisticated wall motion analysis systems have been validated, they can also be used with the echocardiographic maps to quantify the overall extent of abnormal wall motion.

Conclusion. This report described a technique for quantitatively plotting areas of abnormal left ventricular function on maps of the endocardial surface. The data for plotting both the basic endocardial maps and the abnormal regions are derived from routine echocardiographic studies. This technique for quantifying the spatial extent of ventricular dysfunction should be potentially useful in the investigation of ischemic heart disease and the evaluation of therapies for the resulting wall motion abnormalities.

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References


