The Paradox Image: A Noninvasive Index of Regional Left-Ventricular Dyskinesis

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The paradox image, a functional image of regional dyskinesis derived from the equilibrium (gated) radionuclide ventriculogram, was constructed by subtracting the background-corrected end-diastolic frame from the background-corrected end-systolic frame. In 11 patients showing dyskinesis by contrast ventriculography, the percentage of left-ventricular picture elements containing paradox ranged from 3.6 to 55.8% (21.44% ± 4.45 s.e.m.). In 11 patients with normokinesis and in eight patients with hypokinesis by contrast ventriculography, the left-ventricular picture elements demonstrating paradox were less than 1.1% in all cases. In nine patients with akinesis, the percentage of left-ventricular picture elements containing paradox was 2.05% ± 0.96 s.e.m. and was less than 2% in seven patients. There was also an excellent agreement between the location of dyskinesis on the paradox image and that by contrast ventriculography. The paradox image is a sensitive indicator of left-ventricular dyskinesis and should be useful in the evaluation of patients with suspected left-ventricular asynergy.


Descriptive analysis of left-ventricular asynergy has become routine with the widespread use of contrast left ventriculography (1). This technique has limited applicability, however, in clinical situations requiring serial evaluations of ventricular function and evaluation of critically ill patients. Radionuclide ventriculography provides a noninvasive technique for the serial evaluation of left ventricular function, both at rest and during physiologic and pharmacologic interventions. Quantitative assessment of regional left-ventricular function has previously been based on geometric principles derived from contrast ventriculography. The limitations of these geometric approaches for radionuclide ventriculography include: (a) poor definition of end-systolic chamber margins due to high background activity; (b) the need to view an abnormal wall segment tangentially to appreciate fully the severity of asynergy; (c) difficulty in assessing effects of compensatory hyperkinesis from a tangential perspective; and (d) diminished validity of geometric assumptions regarding left-ventricular shape and volume occurring with asynergy. A number of investigators have described quantitative global and regional indices of left-ventricular function based on changing count rates, a variable that is directly proportional to changes in ventricular blood volume. In this report we describe and evaluate the paradox image, a functional image for the evaluation of left-ventricular dyskinesis.

MATERIALS AND METHODS

Patient population. The study group consisted of 39 patients undergoing routine diagnostic coronary catheterization, referred to the Peter Bent Brigham Hospital for evaluation of chest pain suggestive of angina pectoris. We included in this study patients with normokinetic, hypokinetic, akinetic, or dyskinetic left-ventricular wall motion based on the extent of hemiasis shortening on the contrast left ventriculogram. The equilibrium radionuclide ventriculogram was performed within 24 hr of the
contrast study. Patients with frequent ventricular premature beats (more than 10% of the total beats) or arrhythmia (a variation of more than 200 msec in length of the cardiac cycle) were excluded from the study.

**Radionuclide data acquisition.** In vivo RBC labeling was effected by the antecubital i.v. injection of unlabeled stannous pyrophosphate, followed by 25 mCi of technetium-99m as pertechnetate 15–20 min later (2, 3).

Gated radionuclide angiograms were obtained using an Anger scintillation camera with a high-sensitivity 30° slant-hole straight-bore collimator* (3). Five minutes after injection of the radionuclide, the camera was positioned in the modified left anterior oblique (MLAO) position (30° caudal tilt). The patients were positioned with the long axis of the left ventricle aligned vertically so that it would lie parallel to the y axis on computer matrix displays. Composite low-count (400,000 counts) scintigrams were acquired until the camera obliquity demonstrating the greatest separation of the right and left ventricles was found (typically between a 35 and 40° LAO). Six to ten million counts (approximately 1,000 cardiac cycles) were acquired using a digital computer. Counts were recorded from the area of the detector falling within an inscribed square such that the corners of the square approximated the outer perimeter of the detector’s field of view. Since the detector diameter was 25 cm, the length of each side of the inscribed square was 17.3 cm. Those photoevents falling within the inscribed square and within a 15% window centered on the photopeak of Tc-99m were recorded. The density of picture elements was 13.7 elements per cm², and the average count in the background-corrected end-diastolic left ventricle was 48.3 counts per picture element.

The data were collected using a 64 × 64 matrix, dividing the cardiac cycle into 50-msec frames. A composite cardiac cycle was constructed such that the nth composite frame included those counts falling in a 50 msec window ending (n) · (50 msec) from any electrocardiographic R wave. The resulting composite dynamic study was stored on magnetic disc for further processing. Each 50-msec frame contained between 300,000 and 600,000 counts, with more than 30,000 counts within the left ventricle in the end-diastolic frame in patients with normal heart size.

Analysis of left-ventricular dyskinesia was based on the construction of functional images of left-ventricular paradox, where the degree of paradox for a given matrix cell was graphically portrayed using a 16-shade color display. The presence and extent of paradox in each cell for the 64 × 64 matrix was determined from the end-diastolic (ED) and end-systolic (ES) counts within that cell according to the equation:

Paradox = ES − ED

The end-systolic and end-diastolic frames were defined from the left-ventricular time-activity curve where the frame containing the highest number of counts is end-diastole and that with the lowest count is end-systole.

Construction of the paradox image was initiated by manually tracing the end-diastolic left-ventricular perimeter using an electronic cursor. Errors in the end-diastolic left ventricular outline were then corrected using the ejection-fraction image and stroke-count image (4). The end-systolic perimeter was also traced manually using the end-systolic frame. The end-diastolic left-ventricular perimeter was then corrected in regions where the end-systolic perimeter extended beyond the end-diastolic perimeter. Thus the left-ventricular area used for construction of the paradox volume image was the union of the end-diastolic and end-systolic left-ventricular areas.

An automated computer algorithm (4) was used to define background regions and place them relative to the hand-drawn left-ventricular perimeter. The left-ventricular background per cell was estimated as the mean counts/cell in the three background regions of the end-diastolic frame. This background was then subtracted from each cell of the end-diastolic and end-systolic frames. The background-corrected end-diastolic and end-systolic frames were smoothed using a standard nine-point spatial smoothing algorithm. After smoothing the background-corrected end-diastolic and end-systolic frames, each end-diastolic cell was subtracted from the corresponding end-systolic cell to form the paradox image. No negative numbers were stored in the matrix. Only those cells with (ES − ED) > 0 were nonzero in the image, all others being set to zero. The resulting matrix was then smoothed to provide the final paradox image.

Quantitative measurement of paradox was determined by drawing a region of interest encompassing the left ventricle (Fig. 1). Our preliminary experience demonstrated that inclusion of the four rows of matrix cells

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FIG. 1. Left-ventricular perimeter is drawn with electronic cursor and represents greatest expansion of left ventricle, whether it occurs at end-systole or at end-diastole. For determination of paradox, four rows of cells lying directly inferior to base of heart are excluded.
adjacent to the left-ventricular base resulted in cells demonstrating paradoxical volume in patients without contrast angiographic evidence of asynergy, probably as a result of superimposition of adjacent structures such as the left atrium. These four rows were therefore excluded from the left ventricular region of interest. The extent of paradox was determined both in terms of the number of picture elements within the left ventricle demonstrating paradox and the number of counts within those picture elements. Both the number of cells and number of counts were normalized by dividing by the number of picture elements within the entire left ventricle during end-diastole and the number of counts within the left ventricle during end-diastole, respectively.

Global ejection fraction (EF) was calculated from the total left-ventricular counts during end-diastole and end-systole using the equation:

\[ EF = \frac{ED - ES}{ED - B} \]

where background (B) is the mean counts/cell in three background regions.

**Contrast ventriculographic analysis.** For each contrast angiographic study, hand-traced right anterior oblique silhouettes of left-ventricular end-diastole and end-systole were obtained by a second observer from projected cineangiograms (16 or 35 mm) obtained in the standard 30° RAO projection (5–7). Only the first three beats after contrast injection were accepted for analysis. Beats immediately following a ventricular extrasystole were rejected. After apposition of longitudinal axes of the selected end-diastolic and end-systolic tracings, the end-diastolic axis was quadrisected to define six segmental hemiaxes. The left-ventricular silhouette was then divided into apical, anterior, and inferoposterior regions. An additional transverse axis at the junction of the mid and distal thirds of the end-diastolic long axis defined the proximal margin of the apical region. Anterior and inferoposterior regions were above and below the long axis, respectively.

Evaluation of superimposed end-diastolic and end-systolic silhouettes allowed identification and location of abnormally contracting wall segments. Systolic hemiaxis shortening of less than 25% was considered abnormal (asynergy). Asynergy was classified as hypokinesis (>5% shortening) or akinesis (<5% shortening). Hemiaxis shortening greater than 25% was defined as normokinesis. Paradoxical wall motion was defined as expansion in any region of the left-ventricular wall visible at end-systole.

**RESULTS**

Of the 39 patients in this study, 11 had normal contrast left ventriculography at rest (Group 1). Of these patients, seven had normal coronary arteriography, one patient had hemodynamically significant single-vessel disease (luminal narrowing of >50%), and three had hemodynamically significant three-vessel disease.

In eight patients, hypokinesis was observed on the contrast study (Group 2). One of these patients had single-vessel disease, four had two-vessel disease, and three had three-vessel disease. Hypokinesis involved the apex in six patients, and the anteroseptal segment in two.

In nine patients (Group 3), akinesis was present in one or more segments on their contrast ventriculograms without evidence of dyskinesis. Four of these patients had two-vessel disease, and five had three-vessel disease. Akinesis involved the inferoposterior segment in five patients, the anteroseptal segment in two, the anteroseptal and apical segments in one, and all three segments in one patient.

Eleven patients (Group 4) had dyskinesis in one or more regions on their contrast left ventriculograms. Five of these patients had two-vessel disease, five had three-vessel disease, and one had no significant coronary artery disease. Paradox involved the apex in six cases; the inferoposterior segment in one; the anteroseptal and apical segments in two; the inferoposterior and apical in one; and the apical, anteroseptal, and inferoposterior segments in one patient.

All 11 Group 1 patients had less than five counts and less than five picture elements containing paradoxical activity within the left-ventricular perimeter on the paradox image (Fig. 2). The percentage of total left-ventricular picture elements demonstrating paradox was less than 1% in all cases (0.40% ± 0.11 s.e.m.) (Fig. 3). The paradox fraction (paradox counts divided by background-corrected end-diastolic counts) was 0.0001 ± 0.0001 s.e.m. All eight Group 2 patients had eight cells of paradox or less, or 11 or less counts of paradox within the left-ventricular region of interest. The percentage of left-ventricular picture elements containing paradox was less than 1.1% in all Group 2 cases (0.65% ± 0.13 s.e.m.), and the paradox fraction was 0.0002 ± 0.0001 s.e.m. In seven of nine Group 3 patients, there were ≤10 picture elements containing paradox, and the percentage of total left-ventricular picture elements containing paradox was less than 2%. In the remaining two patients, there were 47 and 62 picture elements of paradox, and the percentages of total left-ventricular picture elements containing paradox were 4.9 and 8.5%. In these two patients, the picture elements were scattered throughout two of the three left-ventricular segments, and the greatest number of contiguous cells containing paradox was 13 in both patients. The mean percentage of total left-ventricular picture elements in Group 3 patients was 2.05% ± 0.96 (s.e.m.), the number of counts of paradox was 23 ± 11 (s.e.m.) (range: 0–102), and the paradox fraction...
(paradox counts ± background-corrected end-diastolic counts) was 0.0005 ± 0.0003 s.e.m.

In patients with left-ventricular dyskinesis evident on contrast ventriculography (Group 4), the number of picture elements containing paradox ranged from 29 to 543. The percentage of left-ventricular picture elements containing paradox ranged from 3.6 to 55.6% (21.44% ± 4.45 s.e.m.). Unlike the Group 3 patients, picture elements containing paradox were contiguous rather than scattered. Thus, in the two patients with less than 5% of total left-ventricular picture elements containing paradox, the number of contiguous picture elements containing paradox was 18 and 30. In the nine other Group 3 patients, there were more than 100 contiguous picture elements each containing paradox. In seven patients, paradox involved 20% or less of the left-ventricular area (Fig. 4). In three patients, however, paradox appeared more diffuse, involving up to 55% of the left-ventricular area (Fig. 5). In the Group 4 patients the number of counts of paradox was 587 ± 188 (s.e.m.) (range: 38–2185) and the paradox fraction was 0.0126 ± 0.0039 s.e.m. (range: 0.0007–0.0472).

There was agreement between the paradox image and contrast ventriculography as to the location of the dyskinesis in all segments demonstrating paradox on the contrast study. In six anatomic segments that were not dyskinetic or akinetic on contrast ventriculography, there were paradoxical picture elements on the radionuclide image. In four of these six segments, however, the number of paradoxical picture elements in that segment was less than 10% of the total picture elements demonstrating paradox. In view of these results, we considered a segment dyskinetic if 10% or more of the total left-ventricular picture elements containing paradox were in that anatomic segment. By these criteria, 16 of 16 dyskinetic segments on contrast ventriculography were correctly identified, while 15 of 17 segments without dyskinesis were also correctly identified.

The correlation between the percentage of total left-ventricular picture elements containing paradox and global left-ventricular ejection fraction was excellent (\(r^2 = 49.64 - 1.04\text{EF}; r = 0.85; S_{xy} = 8.13\)). The correlation between ejection fraction and the fraction of left-ventricular counts demonstrating paradox was poor, however \(r = 0.58\).

**DISCUSSION**

Dyskinetic motion of the left-ventricular wall, occurring as a direct result of ischemia, was first observed by Tennant and Wiggers (8). Dyskinesis has been defined as the paradoxical systolic expansion of a local portion of the left ventricle. During contraction, blood moves into this area and is therefore not available for ejection into the aorta. (9).

With the advent of fluoroscopy and kymography, paradoxical ventricular wall motion could be assessed in man (10). With the widespread use of contrast left ventriculography, quantitative approaches to the study of dyskinesis and other forms of asynergy became possible (1). Recently noninvasive assessment of paradoxical wall motion has been described using the radionuclide ventriculogram and the geometric approaches to the
assessment of asynergy used in contrast ventriculography (11).

These geometric approaches have several limitations. Because they assess changes in the contour of the left ventricle, only the walls tangential to the imaging device are measured. Accuracy is dependent upon accurate placement of the end-diastolic upon the end-systolic image and accurate definition of the ventricular axes. Detection of the ventricular border must be performed accurately, a particular problem for the end-systolic image using the radionuclide approach.

Global and regional left-ventricular ejection fraction can be measured from the change in background-corrected count rate occurring between end-diastole and end-systole. This technique has been used for the evaluation of left-ventricular asynergy. We have previously described the utility of functional maps of ejection fraction in identifying left-ventricular regions demonstrating normokinesis, hypokinesis, or akinesis (4). These images, termed the ejection-fraction images, display the ejection fraction occurring within each picture element of the matrix. The primary advantage of this approach is that it is not limited to evaluation of the ventricle along the tangential walls but views the left ventricle threedimensionally, independently assessing change in blood volume (directly proportional to change in background-corrected counts) that occurs in each region of the left ventricle that is assessed (12).

In the present study, we evaluated the paradox image, a computer-generated functional image displaying changes in count rate occurring between end-diastole and end-systole in those regions in which the count rate increases in systole. Since this technique escapes the geometric constraints of more conventional methods of analysis, we found the ejection fraction correlating more closely with our measure of the percent paradox than with estimates made by contrast ventriculography.

The paradox image appears to be a highly accurate detector of dyskinesia. In the only two patients who had an abnormal paradox image but who showed no dyskinesis on contrast ventriculography, a small number of paradox picture elements were scattered throughout a large area over the left ventricle. This appearance might result because of random noise or because of small, scattered areas of dyskinesia undetected by contrast ventriculography. In patients with dyskinesis on the
contrast study, the dyskinetic segment on the paradox image was localized to a well-defined portion of the left ventricle, usually in the apical segment. Only when global left-ventricular ejection fraction was markedly depressed did dyskinesis extend over a large area of the left ventricle.

The correlation with global left-ventricular function was better when area was used as an index of paradox rather than counts, because the number of paradox counts was very small relative to the background-corrected left-ventricular end-diastolic counts. We therefore consider the percentage of total left-ventricular picture elements containing paradox a better index of left-ventricular dyskinesis than indices based on count rate alone. Indices based on area of paradox do have intrinsic limitations, however. A picture element contributes the same value to the index whether end-systole minus end-diastole is one count or a thousand. Furthermore, area measurements do not take into account the three-dimensional geometry of the left ventricle. Therefore, both area and count indices should be considered in the evaluation of patients with suspected dyskinesis.

In this report we have avoided the term aneurysm up to this point. The gated equilibrium radionuclide ventriculogram is an excellent test of cardiac function. Dyskinesis or paradox are terms that describe cardiac function. Aneurysm is a term describing anatomy. Furthermore, the definition of the term, aneurysm, is not universally agreed upon (13–15); the presence of a surgical neck is required in some definitions but not in others. This distinction is an anatomic one in any case, and radionuclide techniques are poorly suited to make it. Surgical intervention is based on function, however. The indications for aneurysmectomy are the presence of congestive heart failure, arrhythmias, occurrence of systemic arterial embolism, and localized dyskinesis with satisfactory function elsewhere in the ventricle (16). Furthermore, postoperative results depend on preoperative hemodynamics, not anatomy (15). This report suggests that the radionuclide ventriculogram and the paradox image can provide the functional information necessary to evaluate the patient with a suspected aneurysm.

The advantages of the paradox image are that it provides: (a) an accurate noninvasive test for detecting dyskinesis; (b) a precise indicator of the site of dyskinesis; (c) a method for the separation of focal from diffuse dyskinesis; and (d) a quantitative estimate of dyskinesis, permitting comparisons at various times during or following medical and/or surgical interventions.

FOOTNOTE

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REFERENCES