On-line Assessment of Ventricular Function by Automatic Boundary Detection and Ultrasonic Backscatter Imaging

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To provide an approach suitable for on-line analysis of ventricular function, a conventional two-dimensional ultrasound imaging system was modified to detect and track blood-tissue interfaces in real time based on their quantitative acoustic properties. This modification permitted on-line display of the left ventricular cavity area, fractional area change, volumes and ejection fraction on a beat by beat basis.

Images were obtained from 54 patients and 12 normal subjects with broad ranges of ventricular dimensions and systolic function. On-line measurements of cavity areas were compared with off-line measurements of cavity areas (analysis of videotaped conventional two-dimensional imaging of ultrasonic integrated backscatter images). Left ventricular cavity areas measured on-line from short-axis views correlated closely with off-line views as did areas from apical views. On-line fractional area change correlated well with ejection fraction calculated off-line.

More than 70% of patients could be studied adequately with the approach developed. Thus, automatic boundary detection based on quantitative assessment of tissue acoustic properties permits on-line quantitation of ventricular cavity areas and indexes of function. (J Am Coll Cardiol 1992;19:313-20)

Conventional two-dimensional echocardiography is a powerful tool for measuring cardiac chamber dimensions, ventricular wall thickness (1) and quantifying left ventricular function with criteria recommended by the American Society of Echocardiography (2). In clinical practice, however, ventricular function is generally assessed only qualitatively and subjectively because of the impracticality of routine quantification of off-line video image analysis, which requires computer-assisted systems for off-line digital acquisition of selected frames, meticulous frame by frame assessment of endocardial-blood interfaces, experienced observers and labor-intensive procedures. Accordingly, considerable attention has been devoted to developing automated procedures capable of quantifying ventricular function by echocardiography (3-16). Most approaches explored have employed off-line computer-assisted algorithms for outlining and enhancing the ventricular cavity and endocardial-blood interfaces.

We previously equipped a commercially available echocardiographic system with circuitry that provides real time detection and Ultrasonic Backscatter Imaging. The modified system was modified to detect and track blood-tissue interfaces

Methods

Backscatter imaging system. The modified echocardiographic system employed for quantitative integrated backscatter imaging was developed in our institution (17-21) and has been validated by others (22-25). The integrated backscatter imaging system employs a relatively long integration time (3.2 μs) over which each radiofrequency A-line is analyzed. Approximately 100 data points of backscatter are collected along each line and the information is sent to the scan converter for on-line construction of the image in real time. More than 70% of patients could be studied adequately with the approach developed. Thus, automatic boundary detection based on quantitative assessment of tissue acoustic properties permits on-line quantitation of ventricular cavity areas and indexes of function. (J Am Coll Cardiol 1992;19:313-20)
The resulting two-dimensional integrated backscatter image data are therefore considerably smoothed and averaged, resulting in marked reduction of speckle (26) noise in the image. Accordingly, discrimination of the endocardial-blood interfaces or boundaries (those with significantly different backscatter or signal strength) is facilitated, allowing automatic detection and tracking of these boundaries in real time (Fig. 1).

Refinements of previous approaches (8) and the addition of novel software developed for the present study permit the operator to trace a region of interest around the well delineated blood pool cavity (Fig. 2). A calculation and graphics software package then computes and displays the area of the cavity within the region of interest instantaneously (in cm²) along with the fractional area change (in %) for each beat. On the basis of geometric assumptions applicable to the chamber of interest, other variables, such as cavity diastolic and systolic volume, stroke volume and ejection fraction, can be derived readily in real time on a beat by beat basis (Fig. 3).

Normal subjects and patients studied. After written informed consent was obtained, images were obtained in studies of 12 normal subjects and 54 unselected in-hospital and outpatients in whom a conventional two-dimensional echocardiogram had been ordered for evaluation of ventricular function, diagnosis or assessment of the severity of ischemic heart disease with respect to regional or global wall motion abnormalities, evaluation of valvular heart disease or cardiomyopathy (dilated and hypertrophic) or preoperative evaluation of potential lung or heart transplant recipients or patients with peripheral vascular disease.

Procedures. After each conventional two-dimensional echocardiographic view was obtained and recorded (long-axis, short-axis and apical four-chamber views), the respective automatic boundary detection, real time, backscatter images were obtained from each. To implement the automatic boundary detection image, we first obtained the highest possible quality conventional two-dimensional echocardiogram as defined by the optimal delineation of endocardial surfaces. Without any change in transducer placement, the backscatter imaging boundary detection algorithm was acti-

Figure 1. End-systolic conventional four-chamber (left) and automatic real time boundary-detected (right) images. The reduction in noise (speckle) permits the on-line detection and tracking of the sharply demarcated blood-tissue edges.

Figure 2. End-diastolic frame of a four-chamber automatic boundary-detected image (small sector in upper right corner) with a region of interest (solid white line) drawn around the left ventricular cavity. The top graph shows the cavity area computed and displayed instantaneously with calibration marks (in cm²) and with the electrocardiogram displayed for timing purposes. The bottom graph displays the on-line computed fractional area change with calibration marks (in %).
Figure 3. End-diastolic frame of a four-chamber automatic boundary-detected image (small sector in lower left corner) with the region of interest drawn around the left ventricular cavity. The graphs on the right demonstrate from top to bottom the instantaneously measured and displayed cavity area (calibrated in cm\(^2\)), cavity volume (calibrated in cm\(^3\)) and ejection fraction computed beat by beat (calibrated in % units).

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Figure 4. A, Stop frame of a short-axis automatic boundary-detected image displayed in the top two-thirds of the screen, with the on-line instantaneous cavity area graph displayed below. The image displays the circular region of interest drawn through the mid-myocardial echoes (white bright line). B, Stop frame obtained 1 s after A, now with the automatic boundary-detected image engaged but concealed from the image. Thus, the image does not show the borders (concealed), although the graph on the bottom continues to depict the algorithm-detected and computed cavity area (in cm²). The larger (two-thirds of screen size) image without the borders shown is recorded on tape and the cavity measured off-line with use of the trackball. Results are compared with the algorithm-detected areas as displayed and recorded in the same cardiac cycle.

Table 1. Validation of Algorithm

<table>
<thead>
<tr>
<th></th>
<th>r Value</th>
<th>SEE (cm²)</th>
<th>No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nonsimultaneous beats</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>LV area, long axis view</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>On-line ED vs. off-line ED</td>
<td>0.95</td>
<td>1.8</td>
<td>15</td>
</tr>
<tr>
<td>On-line ES vs. off-line ES</td>
<td>0.96</td>
<td>2.0</td>
<td>15</td>
</tr>
<tr>
<td>LV area, short axis view</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>On-line ED vs. off-line ED</td>
<td>0.98</td>
<td>2.8</td>
<td>10</td>
</tr>
<tr>
<td>On-line ES vs. off-line ES</td>
<td>0.99</td>
<td>2.1</td>
<td>10</td>
</tr>
<tr>
<td>LV area, four chamber view</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>On-line ED vs. off-line ED</td>
<td>0.97</td>
<td>3.2</td>
<td>15</td>
</tr>
<tr>
<td>On-line ES vs. off-line ES</td>
<td>0.96</td>
<td>3.7</td>
<td>15</td>
</tr>
</tbody>
</table>

ED = end-diastole; ES = end-systole; LV = left ventricular.

and correlation coefficients were obtained for each comparison.

Ejection fraction on-line. With novel software that was added to the system to permit estimation of the cavity volumes (in ml) based on the area measurements in real time, ejection fraction was displayed as well (Fig. 3). The estimation of ventricular volumes was based on the assumption that volume can be estimated by the ratio of the area of the ventricle in the short-axis view to that in the apical four-chamber view. Our purpose was not to validate this approach for calculation of volume itself. It was simply to compare one estimate of ejection fraction (on-line) with another established estimate of ejection fraction calculated off-line.

Results

We obtained satisfactory studies with automatic boundary detection in 48 (72%) of 66 patients and subjects, with detection and tracking of the endocardial-blood interfaces sufficient to permit analysis of cavity area in at least one of the three echocardiographic views. In addition to these criteria, we considered a study as satisfactory when, while turning the borders on and off during the study, we could ensure that a close estimate of the true endocardium was obtained by the automatic boundary detection method. Of these 48 patients, 13 had global left ventricular dysfunction and 8 had segmental dysfunction. The performance of automatic boundary detection in a single view (short-axis or four-chamber) added approximately 3 to 5 min to the study. Off-line analysis on videotaped data took approximately 10 min per view (selection, freeze frame and analysis).

Validation of the algorithm (Table 1). Results with the algorithm and real time boundary detection system compared with off-line results from recordings of the same boundary-detected images in comparable views are shown in Table 1. The correlations between the two sets of results were close with small standard errors. Thus, the algorithm displayed cavity areas (in cm²) accurately as imaged.

Validation of the method (Table 2). Comparisons between left ventricular cavity areas (end-diastolic and end-systolic)
Table 2. Automatic Boundary Detection Image On-line Versus Conventional Two-Dimensional Off-line Measurements

<table>
<thead>
<tr>
<th>LV area, short-axis view</th>
<th>Mean ± SD (cm²)</th>
<th>Range (cm²)</th>
<th>No.</th>
<th>r Value</th>
<th>SEE (cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LV area, four-chamber view</td>
<td>14.5 ± 7.5</td>
<td>8.2-37.7</td>
<td>13</td>
<td>0.99</td>
<td>1.1</td>
</tr>
<tr>
<td>2D off-line ED</td>
<td>15.1 ± 7.7</td>
<td>10-39.6</td>
<td>13</td>
<td>0.99</td>
<td>0.6</td>
</tr>
<tr>
<td>2D off-line ES</td>
<td>8.5 ± 7.3</td>
<td>3.7-31.2</td>
<td>13</td>
<td>0.99</td>
<td>0.6</td>
</tr>
<tr>
<td>2D off-line ES</td>
<td>8.3 ± 7.6</td>
<td>3.9-32.9</td>
<td>13</td>
<td>0.99</td>
<td>0.6</td>
</tr>
</tbody>
</table>

ABD = automatic boundary detection; 2D = two-dimensional echocardiography; other abbreviations as in Table 1.

analyzed on-line and off-line and measurements of corresponding areas calculated off-line from videotaped conventional echocardiographic images (short-axis and apical four-chamber views) are shown in Table 2. Correlations were close, considering that the data were obtained from different cardiac cycles and without control for the respiration cycle or preclusion of patient motion that may have influenced the two sets of data acquisition differentially.

Additional measurements obtained in the 23 patients with a format that displayed conventional echocardiographic images simultaneously with the computed area tracing obtained with the automatic boundary detection system in the same cardiac cycle are shown in Table 2 and Figure 5. They illustrate the accuracy of the method when the same cardiac cycle is employed for on-line (automated) and conventional off-line measurements (trackball caliper procedure).

**Fractional area change.** Percent change in fractional area was displayed on-line with the automatic boundary detection system for end-diastolic and end-systolic areas from each view. This functional index is derived from the areas directly measured areas (short-axis view) correlated less closely with ejection fraction estimated off-line by the method of Quinones et al. (27) (r = 0.83; SEE = 7%; n = 37 patients). However, the correlation was closer when the fractional area change derived on-line from the apical four-chamber views was compared with ejection fraction estimated off-line by the method of Quinones et al. (27) (r = 0.83; SEE = 7%; n = 37 patients).

**Ejection fraction estimated on-line.** The automatic boundary detection on-line—measured chamber cavity areas were used to extrapolate volumes and ejection fraction as previously described (Fig. 3). The boundary detection on-line measurements of ejection fraction were compared with estimates of ejection fraction off-line. The on-line estimates from the four-chamber view (40.4 ± 15.1%) were not significantly different (p = 0.06) from estimates off-line calculated by the method of Quinones et al. (27) (46.6 ± 17%) in 48 cardiac cycles) and the correlation was less close (r = 0.75). Fractional area change derived on-line by the boundary detection algorithm from apical four-chamber views was significantly lower than that from off-line conventional image measurements (22.9 ± 11.2% vs. 31 ± 12.9%; n = 36; p < 0.006). Thus, despite reasonable correlation (r = 0.77), the automated boundary detection measurements underestimated fractional area change when different cardiac cycles were employed for comparisons.

**Comparison with ejection fraction estimated off-line.** On-line fractional area change (parasternal long-axis views) correlated closely with left ventricular ejection fraction estimated off-line by the method of Quinones et al. (27) (r = 0.84; SEE = 8%; n = 25 patients). On-line fractional area change (short-axis view) correlated less closely with ejection fraction estimated off-line by the method of Quinones et al. (27) (r = 0.63; SEE = 13%; n = 33 patients). However, the correlation was closer when the fractional area change derived on-line from the apical four-chamber views was compared with ejection fraction estimated off-line by the method of Quinones et al. (27) (r = 0.83; SEE = 7.0%; n = 37 patients).
patients and the correlation was close \( r = 0.86 \); \( \text{SEE} = 8.8\% \) (Fig. 6A). The on-line estimates \( (40.6 \pm 15.6\%) \) were not significantly different \( (n = 44, p = 0.06) \) from values determined off-line by the single plane area-length method \( (47.6 \pm 17\%) \) and the correlation was close \( r = 0.87; \text{SEE} = 8.5\% \) (Fig. 6B).

**Discussion**

**Need for quantitation in echocardiography.** Real time automatic detection of the tissue cavity-blood boundary has been an objective of research in two-dimensional echocardiography for more than a decade (3–16). Approaches based on statistical estimation of the brightness of the borders in conventional echocardiograms have been employed for off-line smoothing and approximation of edges to quantify wall motion. The approach we developed is predicated on the quantitative power of measurement of acoustic properties of the tissue in real time. It results in reduction of speckles in the image, permitting detection and improved tracking of the tissue-blood interface. The algorithm we employed is promising for clinical applications and may obviate difficulties encountered with the labor-intensive, time-consuming, off-line method. That method, which we used as a standard for comparison has not gained wide clinical acceptance because of degradation of image quality in freeze frames of video recordings and the impracticality of rapid acquisition of results.

**Current implementation of on-line measurements.** Our results demonstrate the feasibility of performing measurements on-line under clinical conditions in normal subjects and unselcted patients with a wide range of cardiac cavity dimensions and compromise of ventricular function. The algorithm accurately depicts ventricular cavity area \((\text{in cm}^2)\) analogous to a volume curve as evident from the close correlations of algorithm-acquired area estimates with off-line measurements of the recorded boundary-detected image (Table 1). In addition, it characterizes chamber size accurately, as is evident from the high correlations between on-line estimates based on cavity areas and off-line estimates measured in different cardiac cycles. Even higher correlations were obtainable when the areas were measured from the same cardiac cycle by both methods in 23 subjects and patients (Table 2). In the present study, we took a conservative approach and analyzed function on the basis of comparisons between on-line and off-line data from different cardiac cycles obtained within 10 s without control for respiratory motion, patient motion or transducer location and angulation. Despite the impact of these variables, the correlations are close enough to support the view that the on-line method will be a clinically useful alternative to the current tedious on-line analysis or simple subjective interpretation of ventricular function from analysis of conven-
tional two-dimensional echocardiograms (28). The automated procedure should facilitate longitudinal assessments of ventricular function in serial studies in patients with valvular, congenital and coronary heart disease.

Comparison with previous recommendations. Measurement of left ventricular cavity areas and changes in fractional area from the short-axis views has been recommended by the American Society of Echocardiography (2) to quantify ventricular function. With the automatic boundary detection method described here, estimates of diastolic and systolic areas are somewhat lower in absolute terms. The method outlines the papillary muscles and excludes their area from the measurement of cavitory areas, whereas the conventional method ignores space occupied by the papillary muscles, resulting in a higher value for the area. However, values for fractional area change correlate quite well with the two methods.

On-line ejection fraction. In the present study, we utilized a first-step approach to derive estimates of ejection fraction on-line from estimates of ventricular volumes based on a simple approximation of short-axis/four-chamber area ratio. The close correlation between ejection fraction estimated on-line and that measured off-line in patients exhibiting mild to profound ventricular dysfunction of diverse etiologies suggests that the on-line estimation of function provides useful information, even at an early stage of its development.

On-line fractional area change. The on-line fractional area change derived from parasternal long-axis views correlated well with global ejection fraction estimated by the method of Quinones et al. (27). This observation suggests that in many patients, ejection fraction can be estimated quickly from the long-axis fractional area change because most of the shrinkage of the left ventricle during systole occurs in the minor axis. Obviously, patients with apical hypokinesia, akinesia or dyskinesia will require a thorough evaluation of the apical views, as is the case in conventional echocardiographic examinations.

Limitations. The tracking accuracy of the endocardial-blood interface detection appears to be more efficient with the parasternal long-axis than with the short-axis view, probably because the septum and posterior wall boundaries of the region of interest in the long-axis view lie perpendicular to the beam, facilitating detection and tracking. We often encountered difficulties in detecting and tracking boundaries in the parasternal short-axis view, particularly in anterolateral and posteroseptal regions, and in the apical view (lateral wall) perhaps because of anisotropy (29) of myocardium in these zones. The difficulties occurred with similar frequency in patients and normal subjects.

The acquisition of quantitative data using automatic boundary detection requires meticulous attention to the transmit-gain and time-gain compensation controls to ensure that the endocardial edges visualized on conventional images are being detected and tracked by the novel algorithm.

Validation of ejection fraction. The method of Quinones et al. (27) for determining ejection fraction was employed because it is based on multiple linear dimensions and their change with systole, integrated from all cardiac views, rather than on geometric assumptions for ventricular shape. The close correlations obtained when the single-plane area-length method (recommended by the American Society of Echocardiography) (2) was used further confirm the validity of the automated approach.

Conclusions. Our results indicate that quantification of tissue acoustic properties in real time permits detection and tracking of the endocardial-blood interfaces, facilitating quantification of ventricular function on-line. Continued development of this approach should provide assessment of segmental ventricular function under conditions of stress echocardiography and serial monitoring of ventricular performance in an individual patient in settings such as the coronary care unit and operating room (transesophageal imaging), in which changes must be detected promptly so that appropriate adjustments in treatment can be made without delay.

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References

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