Automated Echocardiographic Analysis

Examination of Serial Intraoperative Measurements

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Background: Although transesophageal echocardiography allows continuous intraoperative cardiac monitoring, the technique has been limited by the lack of a method for real-time, quantitative assessment of cardiac chamber size and systolic function. Automated border detection (ABD), based on an analysis of integrated backscatter, is a new technique that is purported to provide real-time, quantitative assessment of left ventricular (LV) areas and fractional area change (FAC). A prospective investigation was designed to assess the accuracy and trending capability of ABD during continuous intraoperative monitoring.

Methods: In 16 patients monitored throughout noncardiac surgical procedures, serial real-time estimates of LV end-diastolic area (EDA), end-systolic area (ESA), and FAC by ABD were compared with paired off-line manual measurements made by two experienced echocardiographers.

Results: There was a high correlation between real-time ABD estimates of LV ESA (r = 0.93), EDA (r = 0.89), and FAC (r = 0.90) to those of the off-line technique. The automated technique systematically underestimated both EDA and ESA, resulting in a small underestimation of FAC. The automated technique demonstrated an accuracy rate of 96% in tracking serial changes in LV area. The technique performed with an 83% sensitivity and 85% specificity for detecting acute changes in LV area.

Conclusions: This analysis of serial intraoperative echocardiograms demonstrates the accuracy of ABD to estimate LV area in real time and to track serial changes in cardiac area during surgery. Although ABD is an automated technique, application by personnel experienced in its operation and an echocardiographic system that includes lateral-gain adjustment controls are recommended for its optimal performance.

(Key words: Monitoring. Intraoperative: echocardiography. Heart: left ventricle.)

RECOGNITION of the limitations of pulmonary artery pressure monitoring and technical advances in the quality of two-dimensional (2-D) imaging and color flow Doppler have increased the use of echocardiography in perioperative care.1–3 Although transesophageal echocardiography (TEE) allows continuous intraoperative monitoring, the technique has been limited by its lack of real-time, quantitative assessment of cardiac preload (end-diastolic area [EDA]) and systolic function. Echocardiographic interpretation is based on subjective visual assessment of real-time images or time-consuming, off-line measurements that require manual tracings of still images. Automated border detection (ABD) is a recent advance in echocardiographic techniques that, by analysis of the integrated backscatter of unprocessed radio frequency data, can define endocardial borders and allow calculation of ventricular cavity areas in real time.

The performance of ABD has been examined in the laboratory setting4,5 and under clinical conditions providing a “snapshot” assessment of a patient at a specific point in time.6–9 The clinical applicability of ABD for continuous, intraoperative monitoring of left ventricular (LV) function throughout the course of surgery has not been evaluated. Consequently, the validity of automated TEE analysis during intraoperative alterations in ventricular loading conditions, contractile function, and probe position remains unresolved. To establish the accuracy and trending capability of continuous ABD monitoring of cardiac function, we compared serial LV cavity area measurements measured in real time during surgery by ABD with postoperative off-line measurements of the same data by experienced echocardiographers.
Materials and Methods

After approval from the human investigations committee and informed consent had been obtained, 27 consecutive patients scheduled for noncardiac surgery and general anesthesia at the Department of Veterans Affairs Medical Center (West Haven, CT) were studied. Exclusion criteria were the presence of esophageal disease, coagulopathy, or patient refusal to participate in the study. The first 5 patients in the study were treated as a pilot group so to familiarize the investigators with operation of the ABD system, including positioning of the region of interest and adjusting the time and lateral-gain control settings for optimal endocardial tracking. Data from these patients were not included in subsequent analysis.

TEE was performed with a Sonos 1500 (Hewlett-Packard, Andover, MA) system equipped with a 5.0-MHz omniplane probe. The Sonos 1500 features lateral-gain control over operator-selected vertical sections of the 2-D echocardiographic image and a proprietary ABD system (Acoustic Quantification, Hewlett-Packard). The Acoustic Quantification system uses the integrated backscatter from the unprocessed radio frequency signal to define the acoustic interface between the cardiac blood pool and neighboring tissues and structures. It is the differences in integrated backscatter between blood and myocardium that enables the Acoustic Quantification system to define the endocardial border in real time. The Sonos 1500 displays a heightened trace of the endocardial border; a digital waveform of the estimated cross-sectional area of the blood pool; and beat-to-beat numerical calculation of EDA, end-systolic area (ESA), and the fractional area change (FAC): FAC = (EDA - ESA)/EDA × 100 (fig. 1).

After induction of general anesthesia and tracheal intubation, the TEE probe was inserted and a transgastric, transverse plane image of the LV was obtained at either the mid or basal papillary muscle short-axis level. These are the most commonly used imaging planes for intraoperative monitoring as they provide reproducible landmarks and examine myocardium perfused by each of the three main coronary arteries. The area of interest was defined by a tracing encircling the LV image. Endocardial tracking by ABD was improved by adjustments in transducer power output, time-gain control and lateral-gain control settings and the transesophageal probe position was secured by clamp. An intraoperative investigator monitored the echocardiographic images for alterations in cross-sectional view or loss of endocardial tracking. Any adjustments to the TEE probe position or gain settings needed to maintain either the same crossing of the LV or endocardial tracking were recorded by the investigators. Anesthetic technique was selected at the discretion of the clinical care team.

The ABD system provides the operator the option to omit display of the highlighted endocardial border on the 2-D echocardiographic image while ABD estimates of LV area remain on display in the lower half of the screen (fig. 2). We used this feature to allow beat-to-beat comparison of ABD-derived area measurements with subsequent off-line manual tracings of the same 2-D images obtained by investigators blinded to the ABD calculations, which were concealed during off-line analysis. Each data collection set also included a sample of the 2-D image with the ABD highlighted border present. After the initial data set, further data was collected according to the following protocol: (1) every 20 min after the previous measurement, (2) at every change in systemic arterial pressure in excess of ±15%, (3) at every change in ABD area estimates in excess of ±1.5 cm², or (4) during any major surgical manipulations (e.g., aortic cross clamping or deep Trendelenburg position).

The data were evaluated off-line in the echocardiography laboratory. Two investigators (A.C.P. and I.S.C.) without reference to the ABD estimates or recordings, independently evaluated the 2-D images using a calibrated video analysis system incorporated into the Sonos 1500. To correspond with the algorithm used by the system, manual tracings of the endocardial border included papillary muscles.

Fig. 1. Display of automated endocardial border detection, digital waveform of left ventricular (LV) areas, and numeric display of end-diastolic area (EDA), end-systolic area (ESA), and FAC (Sonos 1500, Hewlett-Packard).

Fig. 2. Split-screen display of two-dimensional echocardiographic image (top) and automated calculations (bottom).

To establish a reference for quantitative measurements
AUTOMATED TEE ANALYSIS

![Split-screen display of two-dimensional echocardiographic image (top) and automated border detection (ABD) calculations (bottom).](image)

Fig. 2. Split-screen display of two-dimensional echocardiographic image (top) and automated border detection (ABD) calculations (bottom).

der excluded papillary muscles from the cavity area. Each observer, without reference to the other's measurements, obtained EDA and ESA estimates from two sets of endocardial border detection (ABD). Intraobserver variability was calculated as the SD of the bias from the differences in each observer's measurements from these two cardiac cycles. For examination of interobserver variability and comparisons of ABD with off-line methods, we calculated the mean of each observer's measurements for the two consecutive cardiac cycles.

A third investigator (M.L.), blinded to the off-line measurements, recorded the ABD estimates from the coronary arteries selected for manual tracing as referenced by video frame number. The mean ABD measurements from these two cardiac cycles was used for analysis. In addition, the images with the ABD endocardial trace highlighted were qualitatively evaluated off-line by M.L. to assess the accuracy of true endocardial detection by ABD in the intraoperative setting. The short-axis images were divided into four regions (posterior, lateral, anterior, and septal wall segments). The investigator graded endocardial tracking as successful if the highlighted ABD border was within 5 mm of the endocardial border for greater than 90% of the wall segment and if there were no blood-coded regions outside the LV cavity.

Regression and Bland–Altman analysis was performed to compare matched sets of ABD and off-line measurements. To establish a reference standard for the study, the quantitative measurements made by each of our two experienced echocardiographers were compared by Bland–Altman methods. The mean bias and 95% limits of agreement between the two echocardiographer's measurements was chosen as the reference standard. Subsequently, the mean bias and 95% limits of agreement between the mean ABD measurements and the mean of the measurements from both off-line measurements from both observers were compared with this reference standard. This analysis was applied both to data pooled from the study population as a whole and also to the data of each individual in the study. For LV areas, paired t tests was used to compare mean bias between technique and F test to compare SD of bias. Wilcoxon's signed-rank test was used for comparisons of FAC.

To measure ABD's ability to track changes in LV area during a procedure (trending capability) the difference between successive measurements of EDA and ESA was calculated. This data was subjected to regression and receiver operator characteristic analysis techniques to compare the serial changes in LV areas estimated by ABD with those of the off-line observers. The change in LV area measured by ABD needed to predict an acute change in LV area of greater than 1.5 cm$^2$ as determined by off-line measurements was tested at cutoff values of greater than 0.75, 1.0, 1.25, 1.50, 1.75, and 2.0 cm$^2$. The sensitivity and specificity of each cutoff value to predict an acute change in LV area was used to create a receiver operator characteristic curve.

Results

The study population consisted of 22 men with an average age of 62.9 ± 10.5 yr (range 44–85) and a high incidence of coexisting disease: 11 with hypertension, 2 with status-post myocardial infarction, 1 with aortic stenosis, and 1 with atrial fibrillation. Five patients had LV ejection fraction less than 35%. Thirteen procedures were extraperitoneal or peripheral and nine were intraperitoneal. Adequate short-axis images were obtained in 16 patients (73%). Laparoscopic surgical technique was significantly associated with inadequate short-axis images (5 of 6 patients; P < 0.05). These 6 patients were excluded from further analysis. Once an acceptable image was obtained, ABD was optimized within 5 min for all patients. A total of 132 data points were recorded in the study group.

Scattergrams of a regression analysis comparing the mean off-line LV area estimates from the two observers with those obtained in real time by ABD are displayed...
in figure 3. There was a high correlation between ABD estimates of ESA ($r = 0.95$), EDA ($r = 0.89$), and FAC ($r = 0.90$) to those obtained by the off-line technique. Moreover, the intraobserver variability was significantly less with the automated technique than that obtained by off-line methods ($0.2-0.4 \text{ vs. } 0.4-1.2 \text{ cm}^2; P < 0.05$).

Bland–Altman analysis (table 1) showed that ABD systematically underestimated off-line EDA (mean bias = 1.8 cm$^2$; $P < 0.05$) and ESA (mean bias = 0.7 cm$^2$; $P < 0.05$) determinations resulting in a small and statistically insignificant underestimation of FAC (mean bias = 0.5%; $P$ not statistically significant).

For both EDA and ESA, there was a wider range in the 95% limits of agreement between ABD and off-line estimates than those established by the two off-line observers. Examined over the range of LV cavity areas, the automated technique showed significantly increased disagreement with the off-line technique when ESA was less than 1.0 cm$^2$ ($P < 0.05$). This reflects patients with near cavity obliteration as seen with extreme hypovolemia. When examined on the basis of the patients’ global ventricular function, no significant differences in ABD performance were seen in patients with an ejection fraction less than 35% versus the remainder of the study group ($P$ not statistically significant).

To assess the agreement between ABD and off-line measures for individual patients, we performed bias analysis on single patient data from each of the 16 study participants (fig. 4). Limits of agreement varied considerably among patients. ABD performed within the limits of agreement established by our off-line experts in 8 of 16 (50%) patients for EDA and 10 of 16 (63%) for ESA. Seven of 16 (44%) patients had both EDA and ESA measurements within the defined limits of agreement. To determine those factors associated with poor ABD estimates, the ABD data for each patient was adjusted to compensate for systematic error (e.g., mean bias). Once each patients data was adjusted by subtraction of the mean bias, 123 of 132 (93%) of EDA measurements and 126 of 132 (95%) of ESA measurements fell within the limits of agreement defined by our expert off-line observers. In comparison with the remainder of the data set, data points that exceeded the established limits of agreement had a significantly increased incidence of inadequate ABD tracking of septal wall motion as an isolated occurrence (15 of 15 [100%]) or combined with inadequate lateral wall segment tracking (10 of 15 [67%]) ($P < 0.05$). Thus, failure in endocardial border detection of walls lying parallel to the ultrasound beam was identified as a major source of error in ABD measurements.

The ability of ABD measurements to track changes in diastolic and systolic areas during a procedure was assessed by plotting serial changes in LV EDA and ESA in four-quadrant graphs (fig. 5). Data appearing in the upper right and lower left quadrants of a graph show that ABD tracked the direction of area change properly.

**Fig. 3.** Scattergrams and regression analysis comparing real-time automated left ventricular (LV) area estimates with those obtained off-line.

**Table 1.** Statistical Summary

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean</th>
<th>SD</th>
<th>Median</th>
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</thead>
<tbody>
<tr>
<td>EDA (cm²)</td>
<td>56.2</td>
<td>10.3</td>
<td>55.0</td>
</tr>
<tr>
<td>ESA (cm²)</td>
<td>55.0</td>
<td>9.8</td>
<td>54.0</td>
</tr>
<tr>
<td>FAC (%)</td>
<td>65.2</td>
<td>5.3</td>
<td>64.0</td>
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</table>

**Note:** Automated border detection.

- $t$ = Student’s $t$ test for zero bias.
- $\alpha$ = $p$ value by $t$ test of SD of the bias between
- $\rho$ = by Wilcoxon signed rank.

**Discussion**

Our analysis of serial intraoperatively demonstrates the accuracy of ABD LV area in real time and in tracking area during surgery. ABD estimates showed a high correlation with off-line measures. Furthermore, the data showed less bias to beat variability than off-line observers. The technique standardized both ABD and EDA tracking of septal and lateral walls and was an important contributory factor in patients where ABD error was greater than 5%.

**Fig. 4.** Scattergrams and regression analysis comparing real-time automated left ventricular (LV) area estimates with those obtained off-line.

**Table 1.** Statistical Summary

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**Automated TEE Analysis**

ABD correctly detected the direction and changes greater than 1.0 cm² as did measurements with an accuracy closer operator characteristic and the sensitivity and specificity having significant acute changes to 1.5 cm² (fig. 6). A device that accurately detects changes in LV area will have data in the upper left hand corner of the receiver operating characteristic curve. That is, high levels of only small decreases in specific not statistically significant in detecting acute changes in EDA.

Figure 7 provides a specific example of the use of serial changes in diastolic function in a patient who had marked variability during hip fracture repair because of moderate hemodynamic instability.

Through the use of a 63 procedure, ABD accurately tracks LV area and systolic function.

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Figure 7 provides a specific example of the use of serial changes in diastolic function in a patient who had marked variability during hip fracture repair because of moderate hemodynamic instability.
ABD correctly detected the direction of serial area changes greater than 1.0 cm² as determined by off-line measurement with an accuracy of 96% (85/89). Receiver operator characteristic analysis was performed to assess the sensitivity and specificity of ABD in monitoring significant acute changes in area of greater than 1.5 cm² (fig. 6). A device that accurately tracks serial changes in LV area will have data located toward the upper left hand corner of the receiver operator characteristic curve. That is, high levels of sensitivity lead to only small decreases in specificity. At a cutoff value of 0.75 cm², ABD was 83% sensitive and 85% specific in detecting acute changes in EDA or ESA (table 2).

Figure 7 provides a specific example of ABD's ability to track serial changes in diastolic and systolic areas in a patient who had marked variability in volume status during hip fracture repair because of hemorrhage and volume resuscitation. Throughout the course of this 6-h procedure, ABD accurately tracked wide swings in LV areas and systolic function.

Discussion

Our analysis of serial intraoperative echocardiograms demonstrates the accuracy of ABD both in estimating LV area in real time and in tracking changes in cardiac areas during surgery. ABD estimates of EDA, ESA, and FAC showed a high correlation to manual off-line measurements. Furthermore, the ABD measurements showed less beat to beat variability than those of the off-line observers. The technique systematically underestimated both EDA and ESA. Poor endocardial tracking of septal and lateral wall segments was a significant contributory factor in those measurements where ABD error was greater than expected.

Perhaps more importantly for potential use as an automated monitoring tool, the reliability of ABD in tracking directional changes in LV areas throughout a surgical procedure was excellent, achieving an accuracy of 96%. The technique was 83% sensitive and 85% specific for identifying acute changes in LV area.

Our results have important implications for intraoperative monitoring with ABD. In a study of 25 intraoperative echocardiograms by Cahalan et al., ABD underestimated EDA but significantly overestimated ESA resulting in a marked underestimation of FAC.7 Perez and colleagues, using transthoracic echocardiography, also found that ABD underestimates EDA and overestimates ESA.8 In contrast, our results reveal a consistent

Table 1. Statistical Summary

<table>
<thead>
<tr>
<th>Echocardiographic Measurements</th>
<th>ABD versus Off-line Technique</th>
<th>Off-line Technique Interobserver Variability (bias)</th>
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<tr>
<td></td>
<td>r Value</td>
<td>Mean</td>
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<tr>
<td></td>
<td></td>
<td>Mean</td>
</tr>
<tr>
<td>End-systolic area (cm²)</td>
<td>0.93</td>
<td>-0.7†</td>
</tr>
<tr>
<td>End-diastolic area (cm²)</td>
<td>0.89</td>
<td>-1.8†</td>
</tr>
<tr>
<td>Fractional area change (%)</td>
<td>0.90</td>
<td>-0.5</td>
</tr>
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</table>

ABD = automated border detection.
* P ≤ 0.05 by paired t test for zero bias.
† P ≤ 0.05 by F test of SD of the bias between techniques compared with SD of the bias between off-line observers.
‡ P ≤ 0.05 by Wilcoxon signed rank comparison of SD of the bias between techniques versus SD of the bias between off-line observers.

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underestimation of both EDA and ESA by the technique, resulting in a small underestimation of FAC. We believe these important differences between our results and those of prior studies can be attributed to technological improvements in our echocardiographic system, namely the availability of selectable lateral-gain control. Overestimation of ESA occurs when ABD does not track endocardial motion in systole. This causes the ABD algorithm mistakenly to use the end-diastolic position of the wall during its systolic area calculations and thus overestimate ESA (fig. 8). Our ability to adjust

Table 2. Analysis of Trending Data

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<th>AD Technique</th>
<th>Off-line Technique</th>
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<tbody>
<tr>
<td>Sensitivity</td>
<td>83%</td>
<td>44</td>
</tr>
<tr>
<td>Specificity</td>
<td>85</td>
<td>58</td>
</tr>
<tr>
<td>Positive predictive value</td>
<td>97%</td>
<td>337</td>
</tr>
<tr>
<td>Negative predictive value</td>
<td>97%</td>
<td>346</td>
</tr>
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</table>

Table 2 - Analysis of Trending Data

Fig. 6. Receiver operator characteristic plot to assess the ability of automated border detection (ABD) to detect acute alterations in left ventricular (LV) area greater than 1.5 cm².

Fig. 7. Changes in left ventricular (LV) and end-systolic area (ESA) by automated border detection in a patient who underwent....

gain in the lateral fields improved ABD's tracking of the septal and lateral walls during systole and avoided the significant overestimation of systolic areas seen with prior echocardiographic systems. In fact, when substantial errors were found in an ABD area estimate, loss of endocardial tracking of the septal or lateral wall during systole was present in 100% of cases. Although it does not eliminate this source of error, we believe lateral-gain adjustments markedly reduce ABD error related to poor endocardial tracking of septal or lateral wall segments.

The ability of ABD to track changes in LV area throughout surgery expands the utility of intraoperative echocardiography to monitor both diastolic and systolic performance. LV areas represent the final pathway of interaction between filling pressure and LV compliance and thus avoid many of the limitations based on pulmonary capillary wedge pressure. Two recent studies have examined the validity of LV area measurements during surgery. In one study, the use of LV area as a means of estimating end-diastolic pressures was evaluated. Our results hold promise for developing a technique for providing real-time monitoring of LV performance through automated end-systolic area analysis. The auto-gated transesophageal, end-systolic area technique may be useful for monitoring diastolic function during surgery. We investigated transesophageal, short-axis analysis in five of five patients undergoing coronary artery disease surgery. Limitations in the design of this study included the potential clinical application of the technique.
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Fig. 7. Changes in left ventricular (LV) end-diastolic area (EDA) and end-systolic area (ESA) by automated analysis and by the off-line method in a patient who underwent repair of hip fracture.

Although ABD is an automated technique, echocardiographic expertise and monitoring of its performance are key essentials to accurate measurements. We used dedicated investigators for operation of the echocardiographic system. Clinicians faced with the multitude of responsibilities inherent in anesthetic care may not achieve the same degree of performance with ABD as was obtained in this study. Although we reliably obtained ABD measurements within 5 min in each study patient, additional adjustments to the echocardiographic system, including gain settings and probe position, were required on nine occasions in the 16 patients studied. These changes were required to maintain a consistent cross-sectional image within the area of

and thus avoid many of the limitations associated with measurements based on pulmonary artery capillary wedge pressure. Two recent studies have demonstrated the validity of LV area measurements as a guide to LV filling during surgery. In addition, LV area measurements have been examined in conjunction with systemic arterial pressures to construct pressure–area relations.14 Our results hold promise that automated analysis could provide real-time pressure–area relations that track LV performance throughout a procedure.

The use of LV area as a measure of LV preload has limitations. Among these are errors in extrapolating a volume estimate from a single-plane measure of LV cross-sectional area, particularly in patients with underlying coronary artery disease or LV aneurysm, where abnormal wall segments may not be visible in the plane chosen for monitoring. Additional shortcomings inherent to the TEE technique include potential for obliquity of selected imaging planes to the true anatomic plane and for intraoperative alterations in probe position. The TEE technique is also limited in the setting of laparoscopic surgery. We were unable to obtain adequate transgastric, short-axis views of the LV for ABD analysis in five of five patients with surgical pneumoperitoneum.

Limitations in the design of our study are important in assessing the potential clinical applicability of ABD.

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Fig. 8. Improvement in endocardial border detection with lateral-gain control. (A) Gross overestimation of end-systolic area (ESA) because lateral and septal wall segments were not detected. (B) The same image with lateral-gain adjustment optimized, resulting in marked improvement in the tracking of lateral and septal wall segments.
interest or to correct a decay in endocardial edge detection. Significant errors in LV measurements may result if the ABD system is not monitored by the operator for consistency of the imaging plane. Currently, even automated echocardiographic techniques will require close observation by experienced operators.

The limits of agreement between our two off-line echocardiographers was smaller than that reported from other laboratories. The narrow limits of agreement can be attributed to the high-quality images obtained by TEE and that multiple measurements were taken from each patient. The repeated measurements taken on each patient allowed the off-line observer familiarizing with each patient's echocardiographic anatomy and may have led to greater consistency than observed by observers reviewing a single view. The performance of ABD may be viewed more favorably when compared with other laboratory reference standards.

In summary, ABD provides real-time, continuous monitoring of LV diastolic and systolic function throughout a surgical procedure. The technique reliably detects acute changes in LV areas. Although ABD is an automated technique, application by personnel trained in its operation and an echocardiographic system featuring lateral-gain control are recommended.

References