Anesthesiology
67:630–634, 1987

A Comparison of Hemodynamic Indices Derived by Invasive Monitoring and Two-dimensional Echocardiography

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Intraoperative two-dimensional echocardiography (2D-echo) is useful for monitoring global and regional left ventricular function. The 2D-echo view most frequently utilized during intraoperative monitoring is the short-axis view at the level of the papillary muscles. To determine whether hemodynamic data can be derived from this single 2D-echo short-axis view, 12 patients undergoing coronary artery bypass grafting (CABG) were studied. All patients had normal left-ventricular function preoperatively (ejection fraction = 64% ± 12%). Echo-data were obtained before and after cardiopulmonary bypass (CPB) by epicardial placement of a 5 MHz echo-transducer. The correlation between thermodilution and echo-derived cardiac indices was good (r = 0.8), and not significantly different from the correlation between stroke indices (r = 0.68). A strong positive correlation was established between end-diastolic volume index and echo cardiac index (CI_E) (r = 0.93 before CPB; r = 0.91 after CPB) and end-diastolic area index and CI_E (r = 0.94 before CPB; r = 0.91 after CPB). The pulmonary capillary wedge pressure was not a determinant of cardiac index before or after cardiopulmonary bypass. No correlation was observed between systemic vascular resistance and echo-derived wall stress. These findings demonstrate that, in patients with good left-ventricular function undergoing CABG surgery, 2D-echo provides a better index of left-ventricular preload than conventional invasive hemodynamic monitoring. (Key words: Heart: cardiac output; end-diastolic volume; stroke volume. Measurement techniques: cardiac output. Monitoring: echocardiography. Surgery: cardiac.)

IN CLINICAL CARDIOLOGY, the information provided by two-dimensional echocardiography (2D-echo) has proven useful, and the technique now plays a prominent role in the diagnosis of medical disorders. Two-dimensional echocardiography has also been performed intraoperatively. Epicardial 2D-echo has been utilized to assess ventricular function, valvular function, and distribution of cardioplegia in patients undergoing cardiac surgery.[1–3] Other investigators have utilized transesophageal echocardiography to assess intraoperative regional myocardial function.[4]

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Received from the Departments of Anesthesiology, Medicine, and Surgery, The Mount Sinai School of Medicine, New York, New York. Accepted for publication May 23, 1987. Presented in part at the 1986 Annual Meeting of the American Society of Anesthesiologists, Las Vegas, Nevada.

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The 2D-echo view commonly utilized during intraoperative echocardiography is the short-axis view of the left ventricle at the level of the papillary muscles. Global left-ventricular function can be evaluated by the measurement of end-systolic and end-diastolic short axis areas and calculation of fractional area shortening. The mid-papillary short-axis view is also particularly well suited for detecting ischemia, since the myocardial beds perfused by the three major coronary arteries are well represented at this level of the ventricle.

What remains unclear, however, is whether monitoring the same short-axis view allows derivation of meaningful hemodynamic data. The current study was undertaken to investigate how hemodynamic data, derived by conventional invasive monitoring techniques, compare with equivalent hemodynamic data obtained from an epicardial, mid-papillary short-axis 2D-echo view. Preload and afterload variables were derived by both techniques. The value of various preload indices as determinants of cardiac function was assessed by studying the relationship between these indices and cardiac output.

Materials and Methods

After institutional approval and informed consent had been obtained, 12 patients (six men and six women) scheduled for triple-vessel coronary artery bypass grafting (CABG) were studied. All patients had normal preoperative left-ventricular function with a mean ejection fraction of 64 ± 12% at ventriculography. After placement of a V_5-ECG lead and insertion of radial and pulmonary arterial catheters, anesthesia was induced with diazepam, 0.5 mg/kg, fentanyl, 30 μg/kg, and pancuronium, 0.15 mg/kg, and maintained by infusion of 50 μg/kg fentanyl over 1 h. The patients were ventilated with 100% oxygen and an arterial p_{CO_2} of 40 mmHg was maintained.

Hemodynamic measurements consisted of heart rate (HR); systolic (SAP), diastolic (DAP), and mean arterial pressure (MAP); mean pulmonary arterial pressure (MPAP); pulmonary capillary wedge pressure (PCWP); central venous pressure (CVP); and cardiac output (CO) in triplicate by thermodilution. Cardiac output determinations were repeated until three consecutive measurements with less than 10% variability were obtained. The thermodilution cardiac index (CI_T), stroke index (SI_T),

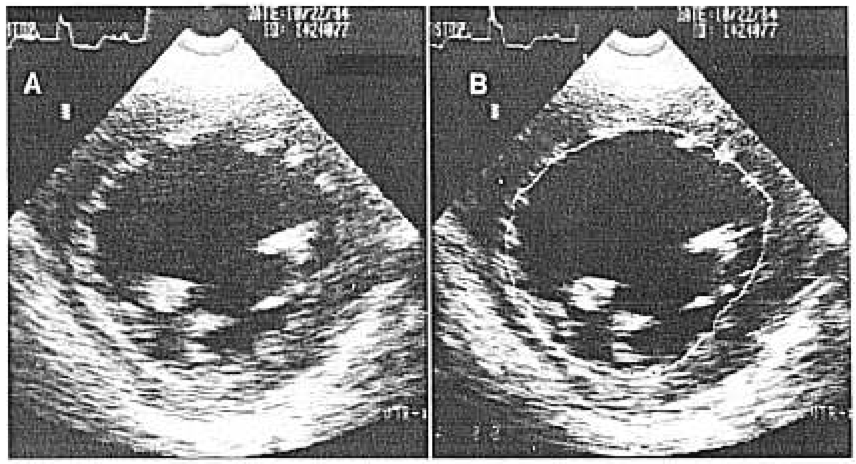

FIG. 1. *A.* Short-axis 2D-echo view at the level of the papillary muscles. *B.* Identical view after tracing of the endocardial edge.

and systemic vascular resistance (SVR) were calculated with standard formulae. 2D-echo data were acquired by placing a 5 MHz transducer (Mark 6000, ATL®, Bellevue, Washington) on the epicardium and recording short-axis views of the left-ventricle at the papillary muscle level.

The mechanical 2D-echo transducer was immersed in sterile gel, covered with a sterile plastic drape, and held on the epicardium by the surgeon. An echocardiographer was present to verify that an optimal circular ventricular view was obtained at the mid-papillary muscle level.

Hemodynamic and 2D-echo data were recorded simultaneously after pericardiotomy and 5, 10, and 15 min after completion of cardiopulmonary bypass. Ventilation was briefly interrupted for the duration of the measurements.

The 2D-echo data were stored on videotape and subsequently analyzed using a computerized digitizing system (CardioRevue®, Diasonics, Salt Lake City, Utah). In each measurement period, four sequential cardiac cycles were selected by a "blinded" investigator. The end-systolic and end-diastolic views of each cardiac cycle were defined as the smallest and largest short-axis views, respectively. The end-diastolic assignment was verified by comparison with the peak of the R wave on a synchronous ECG signal.

The end-systolic and end-diastolic short-axis views of each contraction were then traced at the endocardial edge (trailing edge to leading edge), excluding the papillary muscles and finer trabeculations (fig. 1). The computed short-axis areas (SA) were averaged for the four cycles.

The end-systolic (ESAI) and end-diastolic area indices (EDAI) were calculated using body surface area. End-systolic and end-diastolic areas were also converted to end-systolic and end-diastolic volumes using a modified ellipsoid model: $V = (SA)^{3/2}(36 + SA)/(12 + SA)$.[5] The calculated volumes were used to compute end-diastolic volume index (EDVI), end-systolic volume index (ESVI), echo stroke index (SI_E), and echo cardiac index (CI_E). In addition, for each end-diastolic view, the left-ventricular end-diastolic wall thickness (WT) and intracavitary diameter (LVD) were measured on two perpendicular axes (antero-posterior and septo-lateral). Using these variables, meridional end-systolic wall stress (WS) was calculated with a modification of the Laplace equation: wall stress = $(1.33 \times 0.25 \times SAP[LVD])/WT[1 + WT/LVD]$.[6] Relationships between selected indices were evaluated using a Pearson product-moment correlation and least square linear regression. The statistical significance of differences between correlation coefficients was assessed using Fischer's Z values.[7]

Results

In all patients, short-axis views suitable for analysis were easily obtained. The cardiac index measured by thermodilution (CI_T) correlated well with the cardiac index measured by 2D-echo (CI_E) [$r = 0.8$; $P < 0.001$; standard error of the estimate $S_{y \cdot x} = 0.52$] (fig. 2). The correlation between stroke indices was slightly lower ($r = 0.68$; $P < 0.001$; $S_{y \cdot x} = 4.75$), but the difference

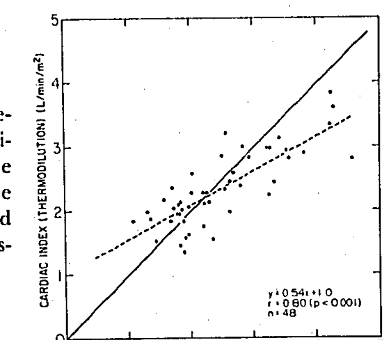

FIG. 2. Correlation between echo and thermodilution cardiac index. The solid line represents the line of identity, while the dashed line represents the regression line.

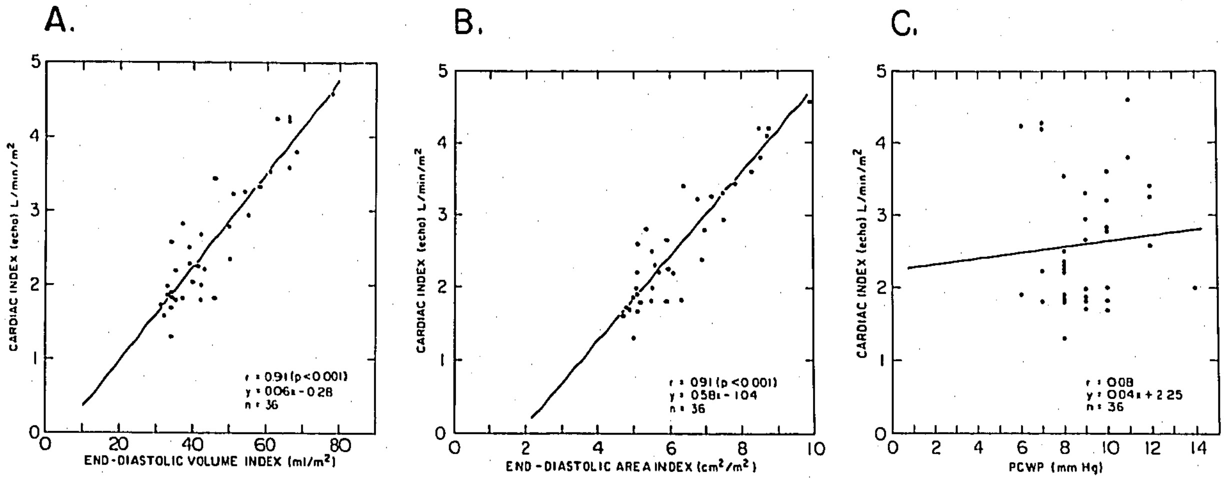

FIG. 3. Correlations between post-CPB EDVI, EDAI, PCWP, and echo-derived cardiac indices (see text).

between the two correlation coefficients was not statistically significant (NS).

Utilizing conventional hemodynamic measurements, the left-ventricular preload is commonly represented by the pulmonary capillary wedge pressure, while, with 2D-echo, it can be represented as end-diastolic area (EDAI) or end-diastolic volume (EDVI). Correlations between the PCWP and either EDAI or EDVI were non-significant. The conventional index of afterload is the systemic vascular resistance, while a different index of afterload, wall stress, can be derived by echocardiography. In our patients, the correlation between these two indices was poor ($r = 0.34$; $P < 0.02$).

To establish whether any of the three preload indices (PCWP, EDAI, and EDVI) was a more sensitive determinant of cardiac index, each was correlated with the echo and thermodilution cardiac index. Before and after cardiopulmonary bypass, a strong positive correlation was established between EDVI and CI_E ($r = 0.93$, $P < 0.001$ before CPB; $r = 0.91$, $P < 0.001$ after CPB) (fig. 3a) and between EDAI and CI_E ($r = 0.94$, $P < 0.001$ before CPB; $r = 0.91$, $P < 0.001$ after CPB) (fig. 3b). No significant correlation was found between PCWP and CI_E at any time ($r = 0.1$, NS before CPB; $r = 0.08$, NS after CPB) (fig. 3c). Similarly, significant correlations were obtained between EDVI and CI_T ($r = 0.6$; $P < 0.001$ before and after CPB) and between EDAI and CI_T ($r = 0.6$; $P < 0.001$ before and after CPB), while no significant correlation was established between PCWP and CI_T ($r = 0.3$, NS before CPB; $r = 0.1$, NS after CPB).

Discussion

Intraoperative echocardiography has been used with increasing frequency over recent years. In initial reports, M-mode ultrasound was primarily utilized to study ventricular function during induction of anesthesia[8,9] or during open heart surgery.[10] Since then, multiple applications of 2D-echo have been reported including detection of myocardial ischemia,[11] recognition of air embolism during neurosurgery,[12,13] or cardiac surgery,[14] and in a number of pharmacological studies.[15,16] Few investigations of intraoperative cardiovascular function, however, have compared the echo-derived indices of function with those obtained by conventional hemodynamic monitoring techniques or have attempted to establish the relative value of either technique. In the present study, patients with normal preoperative left-ventricular function were studied before and after CPB by simultaneous epicardial 2D-echo and conventional hemodynamic techniques. Although, for intraoperative echocardiography, the transesophageal approach presents several practical advantages over the epicardial approach, the short-axis views obtained by either technique are quite similar. In an earlier study, we have demonstrated good correlations between esophageal and epicardial end-systolic and end-diastolic areas.[17]

While 2D-echo allows determination of numerous indices of cardiac function, only those variables which can be measured by both techniques were studied. Cardiac output is one such variable. The determination of cardiac output by echocardiography requires conversion of linear or two-dimensional measurements into units of volume. Matsumoto *et al.* derived cardiac output in 21 patients undergoing open heart surgery who were continuously monitored by transesophageal M-mode echocardiography. They observed a modest correlation between the cardiac output measurement by dye dilution and the echocardiographic technique ($r = 0.72$).[10] In contrast, Terai *et al.*, studying the effects of positive

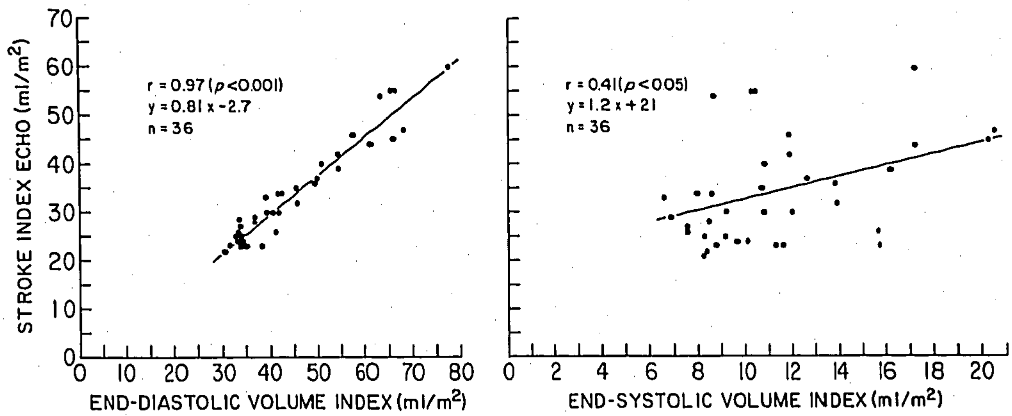

FIG. 4. Correlation between the stroke index (echo) and end-diastolic volume index (left) or end-systolic volume index (right).

end-expiratory pressure on cardiac function using M-mode transesophageal echocardiography, found an excellent correlation (r = 0.97) between M-mode and thermodilution cardiac output.[18]

When using 2D-echo, two perpendicular tomographic views of the ventricle are commonly utilized to calculate the left-ventricular volume by a modification of the Simpsons rule.[19] A long-axis view obtained from an apical two-chamber view and a short-axis view at the level of the papillary muscles are traced at the endocardial border, while a computer calculates the left ventricular volume. When intraoperative echocardiography with either epicardial or esophageal transducer placement is used, a true long-axis view cannot always be obtained, and the length of the ventricle is often underestimated. In the current study, all volume calculations were derived from single short-axis views, using Parisi's equation, and no attempts were made to measure the left ventricular long-axis.[5] Although the volume calculations were based on a single short-axis measurement, a good correlation between thermodilution and echo-derived cardiac index was observed in the studied population. As cardiac output derived from 2D-echo volumes is influenced by regional wall motion abnormalities (RWMA), the less than perfect correlation between CI_E and CI_T may, in part, be a reflection of undetected RWMA. While no RWMA were detected intraoperatively on the observed short-axis views, these could not be excluded for the other sections of the left-ventricular chamber which were not under observation.

The slope of the regression line between CI_T and CI_E indicates that at low cardiac index values, CI_E tends to be smaller than CI_T, while, at high cardiac indices, the reverse occurs. With the trailing edge to leading edge method of endocardial delineation, the short-axis area is underestimated, and, the smaller the measured area, the more significant the underestimation. The lower CI_E values at low cardiac indices can, in part, be accounted for by this mechanism. Pelletier *et al.* have demonstrated that, at high cardiac indices, thermodilution underestimates aortic blood flow, providing an explanation for the discrepancy between CI_T and CI_E which we observed at higher values.[20]

The lack of correlation between the PCWP and EDAI or EDVI has previously been demonstrated by other investigators. Using a coaxial cardiac scintillation probe, Ellis *et al.*[21] have shown the absence of correlation between PCWP and EDVI in patients undergoing myocardial revascularization. Similar results were obtained in post-CABG patients and non-surgical patients in the coronary care unit using gated blood pool scintigraphy.[22] The current study confirms the observation by these last investigators that, particularly in the post-CPB period, PCWP does not provide a reliable indication of preload and does not allow good prediction of cardiac index.

As the echo stroke index is derived from the difference between the EDVI and the ESVI, the interpretation of the high correlation between EDVI and CI_E could be questioned. Study of the correlations between EDVI or ESVI and echo stroke indices demonstrates, however, that the correlation between EDVI and stroke volume indices is excellent (r = 0.97, $P < 0.001$), while the correlation between ESVI and SI_E is poor (r = 0.41, $P < 0.05$) (fig. 4). The difference between the two correlation-coefficients was highly significant ($P < 0.001$). Since ESVI and EDVI are of the same order of magnitude, the value of the stroke index depends in roughly equal manner on each of these variables. One must, therefore, assume that the close relationship between EDVI and SI_E is physiologic rather than mathematical.

For many years, visual observation of cardiac size has been one of the methods used by anesthesiologists and cardiac surgeons to assess cardiac function after CPB. Limitations of this technique are that the assessment is non-quantitative and that the view is primarily restricted to the right ventricle. 2D-echo, however, allows quantitative determination of left-ventricular size, and, in the current study, end-diastolic size, determined by 2D-echo, was shown to be a very good predictor of cardiac output. Thus, in the differential diagnosis of low cardiac output after cardiopulmonary bypass, intraoperative echocardiography provides useful information regarding the left-ventricular preload. This information, when combined with the visual assessment of 2D-echo global and regional ventricular function should facilitate the institution of appropriate therapy.

Left ventricular wall stress is an index of afterload which reflects the combined effects of peripheral loading conditions and intrinsic cardiac properties. Systemic vascular resistance, on the other hand, only reflects the peripheral vasomotor tone and ignores the pulsatile component of afterload. In dogs, Lang *et al.* have demonstrated that discordant changes in wall stress and SVR can occur during pharmacologic interventions, and have concluded that SVR is an unreliable index of afterload.[23] The current study confirms the lack of correlation between wall stress and SVR, but does not allow us to assess the relative value of either variable.

In conclusion, the value of echocardiography in the hemodynamic assessment of patients with normal left-ventricular function undergoing CABG resides primarily in its ability to provide a good index of left-ventricular preload. The end-diastolic volume can readily be estimated in the operating room by the delineation of the end-diastolic short-axis area. The end-diastolic volume or areas recorded in this manner are valid determinants of cardiac index. Wall stress, an index of afterload which can be determined with echocardiography, does not correlate well with systemic vascular resistance. The use of meridional wall stress, rather than systemic vascular resistance, as an index of afterload in the perioperative management of surgical patients needs to be further investigated.

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