Evaluation of the Velcom-100 Pulse Doppler Cardiac Output Computer*

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The use of Doppler ultrasound as a means of obtaining cardiac output (CO) measurements quickly, easily, and noninvasively has been made possible by recent technologic developments. We evaluated a new pulse Doppler ultrasonic unit (Velcom-100, Waters Instruments, Inc) in the Surgical Intensive Care Unit at the University of Michigan Medical Center. Accuracy of this device was determined by comparison of CO results obtained from the Velcom-100 (CO₂) against those of conventional thermal dilution cardiac output (CO₁) measurements. Twenty-six postoperative patients were used for this study, ranging in age from 20 to 82 years old. Initial studies prior to in vivo standardization demonstrated a significantly lower result (p = 0.039) for the Velcom-100 with a mean difference of 0.86 L/min (CO₂ - CO₁). This comparison was significantly improved in subsequent studies following in vivo standardization (CO₂ - CO₁ = 0.02 L/min, p = 0.646). Linear regression analysis showed a significant, positive correlation between the two results (r = 0.85, p < 0.05) indicating an excellent trending capability for the Velcom-100. Our evaluation found the Velcom-100 to be user friendly, allowing rapid training of ICU technicians and applicability for postoperative monitoring.

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CO = cardiac output; CO₂ = cardiac output results obtained from the Velcom-100; CO₁ = conventional thermal dilution cardiac output

The clinical importance of cardiac output (CO) is well recognized in the treatment of patients with acute myocardial infarction of hemodynamic instability. Current criteria for clinical assessment of hemodynamic performance includes pulmonary artery catheterization and thermal dilution CO determination. Invasive vascular access may result in patient discomfort and further complications such as infection, perforation, or hemorrhage. Given the importance of CO assessment, a noninvasive, easily repeated, and cost-effective CO measurement technique could find universal application in the Intensive Care Unit. Doppler ultrasonography may provide the needed benefits and clinical accuracy for noninvasive monitoring.

The simplest form of Doppler instrumentation is continuous-wave Doppler. In a continuous-wave Doppler, the transducer continuously propagates sound into the body. The receiving electronics detect any signal of different frequency from that of the transmitter. A more complicated design is represented by pulse Doppler. Pulse Dopplers require additional circuitry to locate a range gate that corresponds to the listening depth of the Doppler. The important advantage of these systems is their ability to measure signals at a precise depth.

Recent technologic developments by Waters Instruments Inc have made possible a pulse Doppler ultrasound (Velcom-100) designed to determine stroke volume and CO. The purpose of our study was to evaluate this prototype device for application in intensive care areas.

PRINCIPLES OF OPERATION

Doppler ultrasound can be defined as a frequency shift of ultrasonic signal reflected from moving structures within the body. If ultrasound is transmitted into the body and reflected from a stationary medium within the body, no change in the frequency occurs. However, if the reflecting surface (blood, for example) is moving toward or away from the receiver, then the velocity of the moving surface will correspond to the change in the ultrasonic frequency. Such change can be mathematically calculated to determine the velocity of blood flow. The primary characteristics that affect the propagation of the ultrasonic signal are speed of sound in the medium, the magnitude of the ultrasonic attenuation coefficient, and the density of the tissue.1 The operational characteristics of the Velcom-100 are defined in the operator manual.2 The following section offers a brief overview of this unit.

The Velcom-100 is a range-gated ultrasonic device employed to measure the velocity of ascending aortic blood flow from the suprasternal notch and use it to calculate CO and stroke volume (Fig 1). The method employed by the Velcom-100 consists of insonating a "sample volume" in the ascending aorta with an ultrasonic "pulse." The Doppler shift signals employed by the Velcom-100 are within the audio range and used to drive an audio speaker. Detected velocities

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are displayed in real-time on a visual bar graph display. The operator positions the probe to locate the best signal based on the Doppler sounds and the signal appearance on the bar graph display.

The Velcom-100 employs a sophisticated processing technique and computer architecture to determine the average waveform as well as the heart rate (HR). These are combined with the aortic diameter (D) to determine cardiac output (CO) in liters per minute as described below:

\[ CO = HR \times \pi \times D^{5/4} \times \int V(t)dt \]

where \( V \) is the blood velocity.

From this formula it is evident that CO is sensitive to small variations in aortic diameter, since this value (and any error) is squared. The Velcom-100 obtains aortic diameter information from one of three possible sources. If the actual aortic diameter is known from an M-mode aortic root measurement, this value can be entered directly into the Velcom-100. With no such prior knowledge, height, weight, and age are entered, and the Velcom-100 estimates aortic diameter from a standardized nomogram. Also, the Velcom-100 can determine aortic diameter if CO is known from an independent source. The independent value is entered, and the Velcom-100 "back calculates" aortic diameter from its own stroke distance and heart rate measurements. This third option provides a mechanism for in vivo calibration.

The Velcom-100 has two operational modes: depth search and acquisition. During the depth search mode, the Velcom-100 automatically varies the gate depth while acquiring data. Signals are sampled at a particular depth while the operator looks and listens for the highest velocity signal and manipulates the probe in the suprasternal notch. The Velcom-100 provides the operator with pattern recognition feedback by briefly displaying an "S" to the right of the bar graph following any systole that meets its acceptance criteria. The depth with the highest mean peak velocity, and at which acceptable aortic flow was identified, is chosen as the optimal depth.

During the acquisition mode, signals are again sampled at the depth of choice until 12 waveforms are observed that collectively and individually meet certain pattern recognition criteria. When the pattern recognition criteria are met, the real-time examination is completed. Twelve systoles are used to ensure that beat-to-beat variations in stroke volume due to respiration are averaged out. The 12 representative waveforms are averaged, via maximum correlation, to form a single representative waveform.

Initial measurement time varies, but generally requires 10 to 15 minutes for the depth assessment and repeated CO determinations. Subsequent measurements are typically very rapid and easy. In addition to CO, the Velcom-100 determines the patients' stroke volume, heart rate, stroke distance, maximum velocity, acceleration, and ejection time of the left ventricle. These additional parameters may be of benefit for assessment of ventricular dysfunction.

**METHODS**

All patients admitted to the Surgical Intensive Care Unit at the University of Michigan Medical Center were considered potential candidates for participation in this evaluative study. Patients without existing pulmonary artery catheters or inaccessible suprasternal notches (due to dressings, tracheostomy, etc) were excluded. A total of 26 patients, ranging in age from 20 to 82 years old, were enrolled following informed consent.

Four patients (four measurements) originally enrolled were excluded from data analysis because they exhibited an aortic blood velocity in excess of physiologic bounds which indicates inappropriate probe position or gate selection. Of the remaining 22 patients, nine had a single comparative study performed while 13 patients (61 measurements) had two or more studies. Eight of the 13 patients had at least three paired comparisons.

All of the patients were originally studied using the aortic diameter nomogram employed by the Velcom-100. Following the initial Velcom determination, the aortic diameter was back-calculated from the thermal dilution CO measurement. The back-calculation of the aortic diameter is a feature of the Velcom-100 microprocessor program. This process allowed comparison of aortic diameter estimates, recalculation of the original output data, and a method for in vivo standardization of the initial CO. Subsequently, any "true" change in CO should produce a similar change in both units.

The initial test results used for in vivo calibration of the Velcom-100 were analyzed by paired t test separately from subsequent studies. The association between CO1 and CO2 measurements was analyzed using linear regression. A p value less than 0.05 was considered statistically significant for this study.

**RESULTS**

Table 1 shows the differences in CO, stroke volume, aortic diameter estimate, and heart rate obtained by thermal dilution and pulsed Doppler prior to in vivo calibration. The CO and aortic diameter were significantly different (p = 0.039 and p = 0.018, respectively). The mean difference in CO between the two techniques was 0.86 L/min and 8.0 ml/min for stroke volume. Comparison of the remaining studies using
Table 1—Comparison of Initial (before In Vivo Standardization) Cardiac Output, Stroke Volume, Aortic Diameter Estimate, and Heart Rate for Thermal Dilution and Velcom-100

<table>
<thead>
<tr>
<th></th>
<th>Thermal Dilution</th>
<th>Velcom</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cardiac output, L/min</td>
<td>6.79 ± 1.9</td>
<td>5.93 ± 2.02</td>
<td>0.039</td>
</tr>
<tr>
<td>Stroke volume, ml</td>
<td>76.64 ± 26.45</td>
<td>68.64 ± 28.09</td>
<td>0.179</td>
</tr>
<tr>
<td>Aortic diameter, cm</td>
<td>3.56 ± 0.57*</td>
<td>3.23 ± 0.21t</td>
<td>0.018</td>
</tr>
<tr>
<td>Heart rate, bpm</td>
<td>91 ± 18</td>
<td>90 ± 18</td>
<td>0.355</td>
</tr>
</tbody>
</table>

*Aortic diameter obtained based on initial thermal dilution study utilizing the back-calculation mode available on the Velcom-100.

†Aortic diameter was calculated using the nomogram based on the height, weight, and age of the individual.

The in vivo standardization method of calibration is presented in Table 2. As indicated, the in vivo standardization significantly improved the comparison of CO\textsubscript{V} to CO\textsubscript{T}. No significant difference was observed in the comparison of subsequent study results.

Linear regression analysis showed a significant positive correlation between CO\textsubscript{V} and CO\textsubscript{T} when the in vivo standardization was employed \((r=0.82, \text{CO}_V = 0.37 + [0.92][\text{CO}_T], p<0.05)\). The ability to detect relative change in CO demonstrated a similar positive linear correlation as shown in Figure 2 \((r=0.75, p<0.05, \text{change} \text{CO}_V = 0.023 + [0.75][\text{change} \text{CO}_T])\). Since the change in CO\textsubscript{V} was determined using the aortic diameter estimate, this association reflects the ability of the Velcom to trend with thermal dilution regardless of in vivo calibration practice. However, the absolute value of the Velcom output determination remains questionable if the aortic diameter estimate is employed.

**DISCUSSION**

Noninvasive assessment of CO using ultrasonic cardiography has been a goal of research groups for the last decade.\textsuperscript{3,4} Conceptually, Doppler ultrasonography is an easily reproducible technique that eliminates the potential risks associated with invasive techniques. Previous investigations indicate excellent results from this noninvasive method for the measurement of cardiac output.\textsuperscript{6,7}

There are a variety of potential sources of error when determining blood flow by Doppler echocardiography.\textsuperscript{6} This remains true for the Velcom-100, which makes several assumptions about blood flow in the ascending aorta. One assumption is that the angle between the Doppler beam and the direction of flow is 0°. This is a reasonable approximation since cosine (O) is used to compute blood velocity, and, for angles up to ±25°, cosine (O) is always greater than 0.9. In some elderly people, larger deviations of the angle between the ascending aorta and the ultrasonic beam from the suprasternal notch may occur. In these patients, it appears that the heart apex may sometimes rest forward onto the diaphragm, and the axis of the ascending aorta bends away from the suprasternal notch and toward the right shoulder.

A second assumption is that systolic flow in the ascending aorta can be characterized as “plug” flow. Plug flow assumes a blunt flow profile across the aortic flow diameter. The flow diameter is generally stated to be equivalent to the diameter of the aortic valve, which is typically equal to the aortic diameter at approximately 1 cm above the sinus. Violations of this assumption are usually related to the presence of flow turbulence due to stenosis somewhere within the left ventricular outflow tract.

A third assumption is that flow in the aorta only happens during systole, and flow in the aorta always leaves the heart. Blood flow back into the left ventricle due to aortic regurgitation is not measured by the Velcom-100, and hence regurgitation compromises this assumption.

In our experience, these underlying assumptions did not affect the ability of the Velcom-100 to document relative change in CO consistent with the thermal dilution techniques. In its present form, the

![Image](http://journal.publications.chestnet.org/pdfaccess.ashx?url=/data/journals/chest/21630/)

**FIGURE 2.** Plot of change in CO\textsubscript{V} and CO\textsubscript{T} \((r=0.75, p<0.05)\).
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Velcom-100 provides a compact, mobile unit capable of measuring both aortic blood velocities and CO. It provides an easy method for instantaneous assessment of patients without the use of invasive monitoring. The absolute accuracy of this unit remains questionable when using the estimated aortic diameter nomogram. In vivo standardization, through thermal dilution or other measurements of aortic diameter, enhances the absolute accuracy of this unit and whenever possible should be performed to eliminate any errors in output determination associated with aortic diameter estimates. Continued investigation with the Velcom-100 is warranted to fully define its application for emergency and follow-up assessments.

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