Anesthesiology
71:11–15, 1989

Continuous Cardiac Output Determination Using Transtracheal Doppler: Initial Results in Humans

Jerome H. Abrams, M.D.,* Roland E. Weber, Ph.D.,† Kenneth D. Holmen, M.D.‡

Transtracheal Doppler, a procedure developed in the authors' laboratory, provides an estimate of cardiac output in endotracheally intubated dogs. The present study reports initial results in humans with a Doppler probe incorporated into an endotracheal tube. The system was first calibrated by empirically determining $\bar{\phi}$, the angle of the ultrasound beam with respect to the blood velocity vector. For a best least squares fit for $\bar{\phi}$, aortic diameters can be calibrated over a range of 22–37 mm. The calibration was then tested in a separate group of patients using the same empirically derived angle to calculate cardiac outputs. The transtracheal Doppler cardiac outputs show good correlation with those obtained by thermodilution over a range of cardiac outputs, 2.69–8.62 l/min, R^2 = 0.835. (Key words: Heart: cardiac output. Measurement techniques: transtracheal Doppler.)

A NEW PROCEDURE for continuous measurement of cardiac output, in which a Doppler ultrasound probe combined with an endotracheal tube is placed in the trachea, has been described, and the results of feasibility studies on animals have been reported.[1] In this procedure the dimensions of the ascending aorta and the blood velocity in the ascending aorta, proximal to the origins of the aortic arch vessels, are measured. Acoustic contact between the Doppler probe and tracheal wall was satisfactorily maintained, and the lungs were adequately ventilated during measurement of cardiac outputs.

For the application of transtracheal Doppler in humans, the anatomic relationships may be different. Thus, the initial objectives of this study were to confirm the constancy of the anatomy, ensure atraumatic contact between transducer and trachea, and develop positioning procedures that do not interfere with the ventilation of the patient's lungs. The major objectives were to calibrate the Doppler calculations by fitting the data to echocardiography measurements of aortic dimensions in a set of patients and then to test this calibration by comparing transtracheal Doppler cardiac outputs with thermodilution cardiac outputs in a second set of patients.

* Instructor, Department of Surgery and Associate Director, Critical Care, University of Minnesota.

† Applied Biometrics, Incorporated, Minnetonka, Minnesota.

‡ Department of Anesthesia, United Hospitals, St. Paul, Minnesota.

Received from the University of Minnesota, Minneapolis, Minnesota, Applied Biometrics, Incorporated, Minnetonka, Minnesota, and United Hospital, St. Paul, Minnesota. Accepted for publication February 6, 1989.

Address reprint requests to Dr. Abrams: Department of Surgery, University of Minnesota Medical School, Phillips-Wangensteen Building, 516 Delaware Street S.E., Minneapolis, Minnesota 55455.

Materials and Methods

A transtracheal Doppler probe was developed and has been described in detail.[1] It includes a 5-mm diameter ultrasonic transducer at the distal end of the endotracheal tube and a balloon cuff to assure acoustic contact of the transducer with the anterolateral wall of the trachea. The cuff is a prolate ellipsoid that when inflated moves the transducer into contact with the tracheal wall. The electrical leads are contained within the wall of the endotracheal tube.

The electronics monitor used to drive the transducer and process the Doppler ultrasound information was an Applied Biometrics ABCOM® cardiac output computer. The unit operates in a pulsed Doppler mode with a carrier frequency of 5 MHz. When driven by the Applied Biometrics electronics monitor, the ultrasound power output was below the FDA guidelines for cardiac ultrasound use.§ Power measurements were done by an FDA listed ultrasound power testing site. Consistent with FDA guidelines, an area of π (2.5 mm)^2 was used as the area for the power calculations. The continuous cardiac output data were digitized and accumulated for 12-s time intervals to average over the variation in cardiac output that is due to the ventilator cycle.[2,3]

Two groups of patients were studied. In the first group, an independent B-mode echocardiogram was used to obtain ascending aortic diameter. In the second group an angle empirically derived from data in the first group was used to calculate cardiac outputs. Criteria for patient selection in both groups included the following: 1) general anesthesia was necessary; 2) free access to the head and airway was allowed; and 3) patients would be in the supine position. Approvals of the Institutional Review Boards were granted and informed consent was obtained from all patients in both groups. Patients ranged in age from 17 to 69 yr and in weight from 51.4 to 100.0 kg. Eighteen males and eight females were included. The transtracheal Doppler probe was designed to conform to ANSI standards for endotracheal tubes, specification #Z79.14-1983. Probes of 7.0 and 8.0 mm internal diameter were used. Electronics were certified by the bioelectronic engineering departments to have less than the leakage current standards of the Association for the Advancement of Medical

§ 510 (K) Guide for Measuring and Reporting Acoustic Output Diagnostic Ultrasound Medical Devices, December 1985. Guide for Devices and Radiological Health, U.S. Food and Drug Administration.

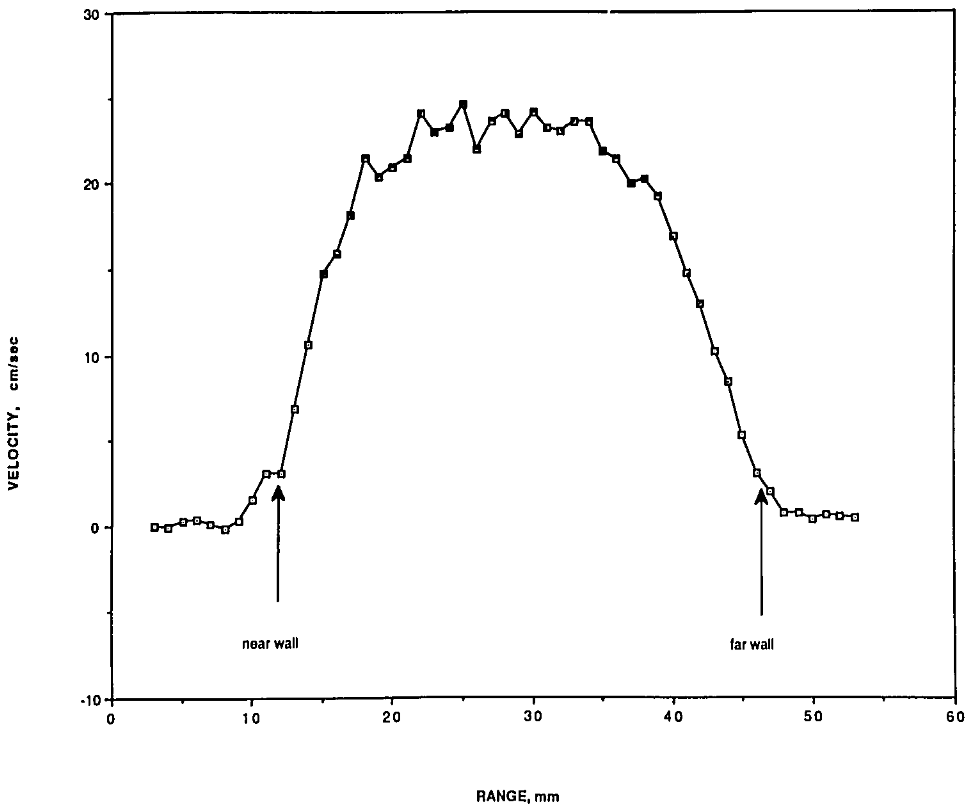

FIG. 1. Change in blood flow velocity in the ascending aorta as a function of distance, labeled range, from the surface of the endotracheal ultrasound transducer. In this example the aortic near wall is 12 mm and the far wall is at a range of 46 mm from the transducer surface. The arrows identify the range at which sound of wall motion was identified.

Instrumentation. Sterilization of the transtracheal Doppler probe was done by ethylene oxide gas sterilization technique in standard fashion.

The transtracheal Doppler probe was inserted as part of routine intubation. A headset, which transmitted the audio representation of Doppler flow signals, was worn to monitor the Doppler flow signals continuously during intubation. In addition, a visual meter to identify both forward and reverse flow was employed. The transtracheal Doppler probe was positioned by translating the probe along its longitudinal axis and rotating the patient's head to maximize both the audio and the visual representation of forward flow as determined by Doppler shift. The transtracheal Doppler probe was secured in place by inflating the cuff and using an endotracheal tube holder. When repositioning of the probe was necessary, the cuff was deflated and the endotracheal tube and the patient's head were manipulated as necessary. The cuff was then reinflated. Breath sounds were obtained bilaterally initially and following repositioning.

Following surgery the transtracheal Doppler probe was removed according to standard criteria for tracheal extubation. Prior to removal, bronchoscopy was performed by one of us (K.D.H.), a staff anesthesiologist, on eight patients to assess the presence or absence of tracheal hyperemia, ulceration, or hemorrhage. In follow-up, inpatients were visited by a staff anesthesiologist. Same day surgery patients were telephoned by a registered nurse to ascertain any anesthetic complications.

The volume flow rate of blood can be calculated from the blood velocity and the cross-sectional area of the aorta,[4,5] both of which are dependent on the angle of the ultrasound beam with respect to flow, ϕ. Since $\phi = \arcsin(d/r)$, an independent aortic diameter (d) was determined by B-mode echocardiography and aortic dimensions (r) were determined from velocity profiles as described elsewhere[1] (fig. 1). The near and far walls were identified as that distance from the transducer where blood velocity approached background. These findings were corroborated by a change in the audio representation of the Doppler shift that had a sound characteristic of wall motion. In the example of figure 1, the near wall is found at a range of 12 mm and the far wall at 46 mm.

The ascending aorta, 2–3 cm distal to the aortic valve, was examined by B-mode echocardiography. The angle ϕ was calculated for 18 patients by allowing the angle to vary through a range of 0–90° in 0.1° increments. An iteration algorithm was then developed to determine the angle ϕ that minimized the residual sum of squares in the relation $\sum x_i^2 = \sum (d_i - r_i \sin \phi)^2$, where $\sum x_i^2$ is the sum of residuals squared, d_i are the independently obtained B-mode echocardiographic aortic diameters, and r_i are the transtracheal Doppler aortic ranges. That value of ϕ resulting in the minimal residual sum of squares was se-

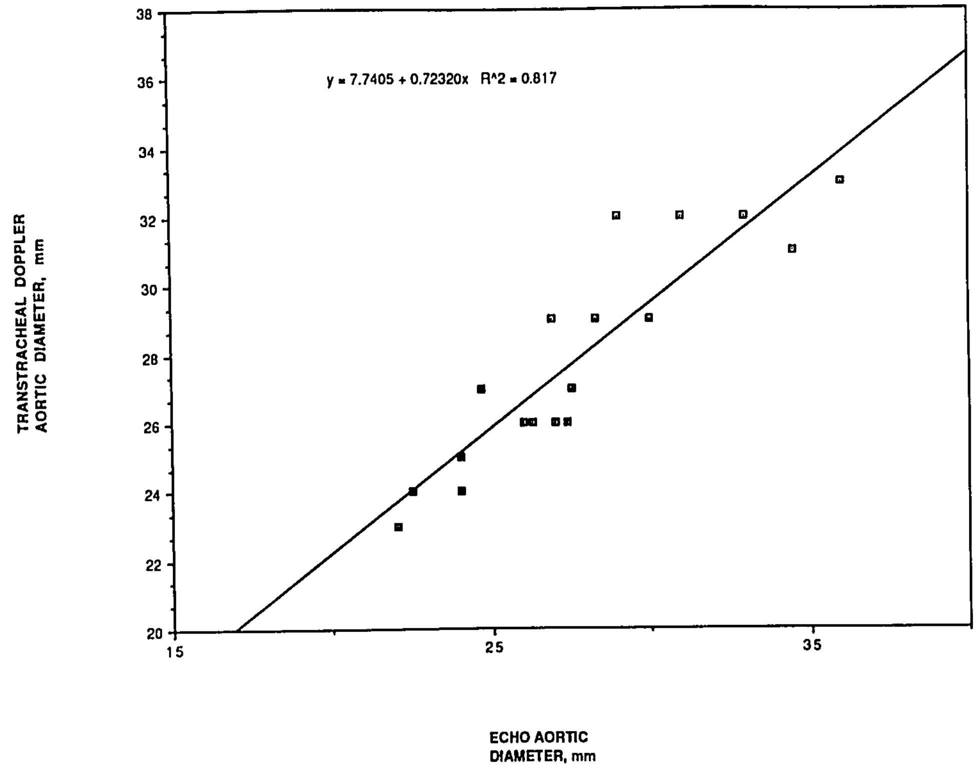

FIG. 2. Diameters of ascending aortas determined from within the trachea by transtracheal Doppler measurements *versus* the diameters measured externally from the surface of the chest by echocardiography.

lected and designated as $\bar{\phi}$. Once the system was calibrated by the determination of $\bar{\phi}$, the main objective of the study, correlation of transtracheal Doppler cardiac outputs with those of thermodilution, was evaluated in an additional eight patients. For these comparisons the blood velocity, $\bar{v}$, was calculated using the angle, $\bar{\phi}$, found from the previous 18 patients.[1,4,5] The cross-sectional area, A, was obtained by assuming the cross section to be a circle.

The volume flow rate, Q, was then calculated and compared with thermodilution cardiac outputs at several different times for each of the second set of eight patients. A regression line was fit to all of the cardiac output data, 40 determinations from eight patients, grouped together.

Results

Because air does not satisfactorily transmit ultrasound, the ability to obtain velocity profiles from the trachea using Doppler ultrasound verifies acoustic contact with the anterolateral wall of the trachea. Results of fiberoptic bronchoscopy revealed no evidence of tracheal hyperemia, ulceration, or hemorrhage. Subsequent patients, in whom tracheal suction was performed through the endotracheal tube, again revealed no evidence of bleeding. Four patients complained of a minor sore throat, of whom three had concomitant insertion of a nasogastric tube. Measurement of cardiac output did not interfere with ventilation of the lungs. No airway complications involving positioning of the transtracheal Doppler probe or measurement of cardiac output were noted.

The best least squares fit for $\bar{\phi}$ in 18 patients was $\bar{\phi}$ = 52.4° ± 3.8° (±SD). Figure 2 presents a scatter plot of the ascending aortic diameter determined by transtracheal Doppler *versus* diameter measured by B-mode echocardiography. Using the angle, $\bar{\phi}$, the diameter of the aorta obtained from transtracheal Doppler data could be fit to the echo diameter over a range of diameter from 22 to 37 mm. A linear regression could be determined over the range of diameters with $R^2 = 0.82$.

Figure 3 presents a scatter plot of transtracheal Doppler cardiac outputs *versus* thermodilution cardiac output. A linear regression line can be fit over a range of cardiac outputs from 2.69 to 8.62 l/min with a correlation coefficient squared, R^2, of 0.84. Another representation of the data is shown in figure 4; each patient's data points are identified and an identity line is shown for convenience.

Discussion

The present study demonstrates that the transtracheal Doppler procedure provides an estimate of cardiac output in humans that compares satisfactorily with thermodilution measurements. Human mediastinal anatomy allows the continuous cardiac output measurement to be performed, using a transtracheal ultrasound window, to measure aortic dimensions and blood velocity.

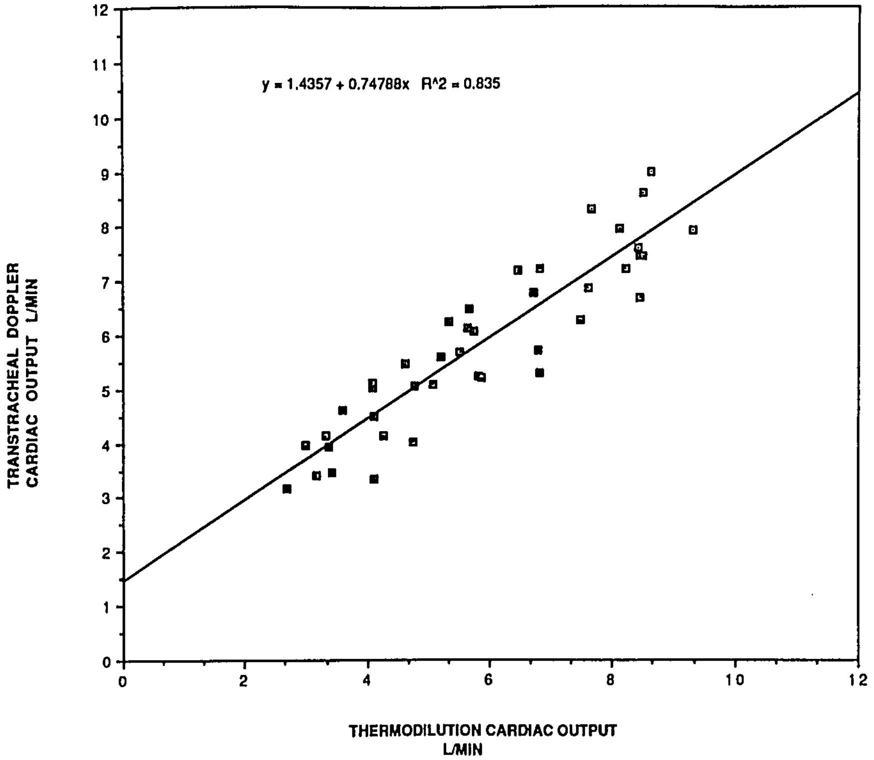

FIG. 3. Transtracheal Doppler cardiac outputs *versus* thermodilution cardiac output.

Sources of error in calculating cardiac outputs include human mediastinal variation, uncertainty in transducer positioning, uncertainty in B-mode echo ascending aortic diameter determination, and uncertainty in thermodilution cardiac output determination. The authors reasoned that if transtracheal Doppler probe positioning were reproducible, human mediastinal anatomy had small enough variation, and if B-mode echo diameter determination

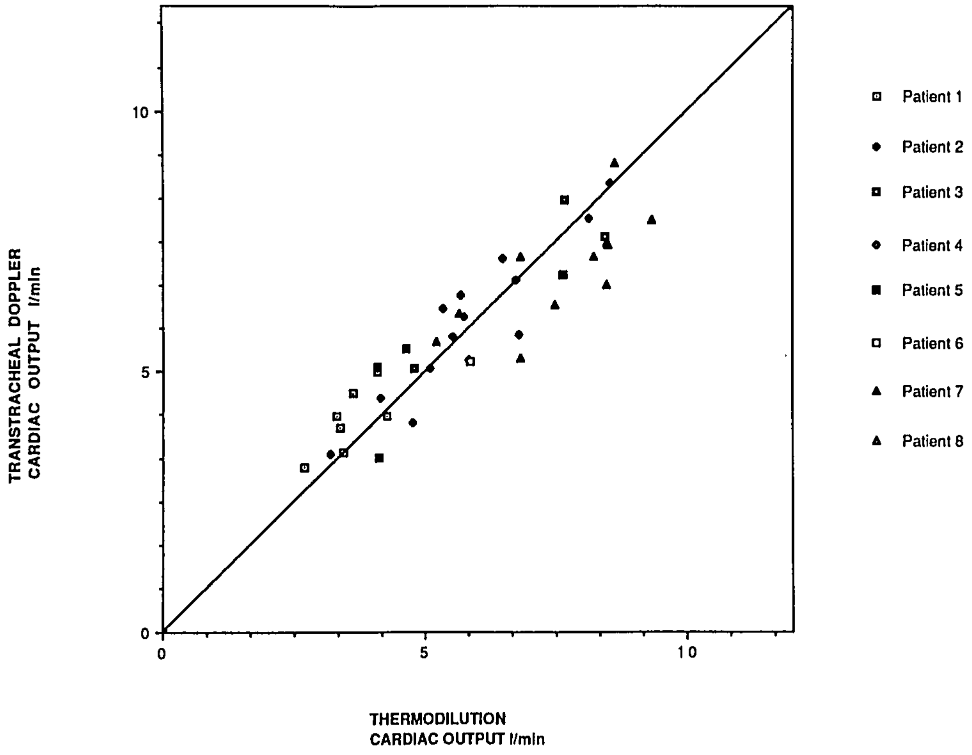

FIG. 4. Transtracheal Doppler cardiac outputs *versus* thermodilution cardiac output. The identity line is shown and data from each patient are identified.

were reproducible, then ϕ would be measurable with small variance. The angle, $\bar{\phi}$, determined by least squares fit, is 52.4° with a standard deviation of ±3.8°. To determine how this degree of uncertainty affects the error in cardiac output determination, an error analysis was performed.

Since Q = vA,

$$\frac{\sigma_Q^2}{Q^2} = \frac{\sigma_{\bar{v}}^2}{\bar{v}^2} + \frac{\sigma_A^2}{A^2}$$

ϕ enters into the calculation of both $\bar{v}$ and A and is the largest component of the error. One finds that $\sigma_{\bar{v}} = 0.09$ and $\sigma_A = 0.11$, for a standard deviation of ±3.8° in the angle ϕ.

Then,

$$\frac{\sigma_Q}{Q} = \left[\left(\frac{\sigma_{\bar{v}}}{\bar{v}}\right)^2 + \left(\frac{\sigma_A}{A}\right)^2\right]^{1/2}$$
$$= 0.14 \text{ or } 14\%$$

An error of 14% in the determination of cardiac output by the transtracheal Doppler method compares favorably with detailed error analysis of thermodilution measurements.[6] The error obtained by this error analysis is consistent with the correlation coefficient obtained by performing a linear regression analysis on the comparison of transtracheal Doppler cardiac outputs with those of thermodilution. Because the slope of the regression line is not unity, systematic experimental error is present but does not prevent calibration of the transtracheal Doppler system. That the slope is less than unity suggests that the correlation may vary with cardiac output. The comparison of transtracheal Doppler cardiac outputs with those of thermodilution is within the experimental error for both methods.

Transtracheal Doppler shows promise as a noninvasive procedure for measuring continuous cardiac output. This procedure unites endotracheal intubation with ultrasound technology to provide simultaneous ventilation of an intubated patient and determination of blood volume flow rate in the ascending aorta.

Reproducibility of human mediastinal anatomy, atraumatic acoustic contact of the ultrasound transducer with the anterolateral tracheal wall, and ability to ventilate lungs without complications, while measuring cardiac outputs, have been confirmed. The present study has demonstrated that an unknown angle in the transtracheal Doppler calculations can be empirically determined to provide a good fit with echocardiography measurements over a range of aortic diameters. A second stage of the study, in a separate set of patients using the same empirically derived angle, has shown good correlation between transtracheal Doppler and thermodilution measurements over a range of cardiac outputs.

The authors thank Abigail Brogden for assistance in obtaining B-mode echocardiograms and the anesthesia and operating room personnel at United Hospitals of St. Paul, Minnesota for their cooperation. E. J. Mikolajczyk and C. T. Hovland contributed tireless and expert assistance. Special thanks to Kathy Kuchenmeister whose endless patience made preparation of the manuscript possible.

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