Laboratory Methods

Aortic Pulse Contour Calculation of Cardiac Output

Constance L. Graves, M.D.,* William M. Stauffer, M.D.,†
Roger L. Klein, M.D.,* Patricia S. Underwood, M.D.‡

A technique utilizing various characteristics of the aortic pressure-pulse contour and the time course of pressure in the thoracic aorta to calculate beat-to-beat changes in stroke volume, heart rate, cardiac output, mean arterial pressure, and peripheral resistance is described. Programmed for on-line data analysis by a digital computer, the method allows an immediate feedback of results while the experiment or operation is still in progress. In addition a time-sharing program enables several investigators with remote substations to use the central computer simultaneously. The technique, compared with more conventional determinations of cardiac output by the Fick and indicator-dilution methods, correlates well under a variety of physiologic conditions. Its use is described as a tool for basic research in anesthesiology as well as a means of monitoring patients in the operating room, recovery room, and intensive care unit.

Rapid estimation of cardiovascular parameters, particularly cardiac output, can be highly useful not only in basic research but also in patient monitoring during and following surgical procedures and in intensive and coronary care units. In recent years the use of computers has shortened the time for analyses and display of results so that the slowest link in the process is often that time involved in the collection of physiologic data.

Methods for measuring the output of the heart, using dye dilution as well as the Fick principle, are based on "steady state" or resting conditions, during which physiologic processes should not have changed for from 40 seconds to one minute for most dye techniques to at least two minutes for the direct Fick technique. These times are additional to those required for calculations. Thus, under rapidly-changing conditions such as hemorrhage, the stroke volume may change appreciably during the time of the determinations so that the values recorded may be only approximations, or mean cardiac output values for a period of several minutes, at best. In addition, the nature of dye-dilution techniques precludes rapidly-repeated or frequent determinations.

"Beat-to-beat" calculations of cardiac output can be performed with surgically-implanted electromagnetic flowmeters, with ballistocardiography, ultrasound, cinefluorography and cineangiography, or with a continuous Fick output recorder.† On the other hand, these methods either are unreliable or do not lend themselves to easy use in intact man under the varied conditions of disease, exercise, or anesthesia.

The purpose of this paper is to describe a method utilizing various characteristics of the aortic pressure-pulse contour for beat-to-beat quantitation of the cardiac stroke volume, its basic principles, its validity, and its uses.

Procedure

A 90-cm-long tellon catheter with an internal diameter of 0.5 mm. is introduced percutaneously under local anesthesia through a thin-walled 18-gauge needle into a peripheral artery. In man the radial artery is used; in the experimental animal the catheter usually is advanced from the femoral or carotid artery. This catheter is attached to a Statham P23Db pressure transducer, and the location of the tip
is sensed by observing the arterial pulse contour traced on a Tektronix memory oscilloscope, the catheter being advanced until the contour has the incisura and dicrotic notch typical of the central arterial pressure wave. Such a contour is shown in figure 1. A second catheter is inserted via an antecubital or femoral vein and threaded into the central venous caval system. This catheter may be used to determine central venous pressure conventionally with a water manometer or may be connected via an appropriate transducer to be measured electronically.

This technique has been programmed for on-line data analysis by a Control Data 3200 digital computer which is located at the Latter-Day Saints Hospital. The output of the pressure transducers is connected to the appropriate input lines of the computer substations where data are converted to frequency-modulated signals and transmitted over telephone lines to the central computer. By means of a time-sharing program several investigators with remote substations are able to use the computer simultaneously. Each substation consists of a memory oscilloscope, an eight-button switch to dial and control the program, an "interrupt" button, and three analog channels for sending data. Seventeen such remote stations are presently in use in three hospitals in Salt Lake City.

To begin operation of the program the investigator dials on his substation switch the code number of the pressure-pulse program, and then depresses the "interrupt" button to call the program into memory. From this point the computer prints on its oscilloscope instructions for supplying the data in proper order and form. The program first requests calibration of the pressure transducer with manometrically-determined pressures of 0 and 100 mm. Hg. This calibration is necessary once only.

Cardiac output is next determined independently by an indicator-dilution technique. Indocyanine green (Cardiogreen) dye is injected through the central venous catheter and arterial blood drawn through a Wood oximeter by means of a Harvard constant infusion-withdrawal syringe. The computer is programmed for immediate calculation of cardiac output upon completion of the sampling. From this datum the computer derives and stores a constant which is applied automatically to all future computations of stroke volume by the pressure-pulse method. Determination of cardiac output by the indicator-dilution method usually is done only once; on the other hand, if repeated checks on the validity of the computer output are desired, determinations can be repeated at any time.

Once these initial calibrations have been performed, the investigator can follow the patient's condition by simply calling the program. The analog-to-digital computer begins to sample the aortic pressure wave at 200 samples per second, identifies the beginning and end of each systole, and carries out appropriate calculations for each heart beat. The output of the program, available in real time, consists of a printout on the face of the station oscilloscope of the average values for stroke volume, heart rate, cardiac output, duration of systole, systolic pressure, diastolic pressure, and the ratio of mean arterial pressure to cardiac output, the peripheral resistance, as well as the plot of the time course of one or more of these variables best by beat. A typical printout is shown in figure 2. If desired, the system may be so arranged that the various parameters will be measured automatically at preset intervals, for example every five minutes.

All values, along with a notation of the time of day, are recorded on magnetic discs. At any time these results may be reviewed as a
Principles of the Pressure-Pulse Method

The method for estimating cardiac output from the pressure pulse contour makes use of the principle that the systolic discharge stretches the aorta and produces an increase in pressure. During diastole the rate of blood draining out of the arterial tree is related to the decline of that pressure. Diastolic drainage occurs, not because of the pumping action of the heart, but solely because of the distensibility of the arterial tree. Thus, if pressure-volume relationships and other mechanical properties of the central arterial system can be specified, stroke volume may be determined from the central arterial pressure.

Some workers have used the velocity of blood flow or of transmission of the pulse wave to the periphery to evaluate aortic distensibility. Hamilton and Remington, after study of the tension-length relationship of rings cut from dead human and dog aortas, believed that the change in volume with change in pressure remained relatively constant and that the important variable was the basic diastolic volume of the aorta, which depended on the body surface area. These workers calculated stroke volume from the aortic pressure pulse using tables for the volume-capacity change of various arterial beds at different pressures and for estimated times of transmission of the pulse wave through these same arterial beds. The correlation of these figures with values derived from simultaneously-performed dye-dilution or Fick techniques in the dog was excellent. In man, with unpredictable variability of age and arterial disease, the correlation was less reliable. Warner and co-workers sought improvement by calculating a factor relating change in pressure to change in volume for each individual. This was done by determining cardiac output at the onset of the experiment using a different method, such as the Fick or dye-dilution technique.

The pressure-pulse program in use at the University of Utah today allows estimation of stroke volume from a single pressure measurement taken in the proximal aorta. Calculations are based on equations and subsequent empirical modifications derived by Warner and co-workers using certain approximations to the real mechanical properties of the central arterial system. So far, the mathematical concepts of the computer model have represented the test data for the conditions investigated accurately.

Validity of the Method

The essential validity of the aortic pressure-pulse method of estimating stroke volume has been tested under a variety of physiologic conditions. Warner compared results of this technique with those obtained in normal man by the dye dilution or the direct Fick method during conditions of rest, tilt, pressurization of the entire surface of the body below the xiphosternum, and exercise. The two series of measurements agreed, with a mean deviation of ±9 per cent. In a later series he compared the results of the pressure-pulse method with direct measurements made with electromagnetic flowmeters which previously had been surgically implanted in dogs. Such comparisons were made under conditions of rest, exercise, infusions of certain drugs (metaraminol, atropine, and neostigmine), and in dogs with complete atrioventricular block in which the heart rate could be varied from 60 to 240 beats per minute. Correlation between the two methods was 0.98.
In our laboratories we have used the pressure-pulse method to determine cardiac output in dogs under general anesthesia and have compared these pressure-pulse cardiac outputs with indicator-dilution outputs at various stages of hypotension occurring with deepening anesthesia. Correlation between the values obtained by the two methods was 0.96. The result of 16 such comparisons in 5 dogs is shown graphically in figure 3.

Uses of the Program

The study of the heart and circulation by the pressure-pulse method is now being extensively used in the cardiovascular laboratories of the Latter Day Saints, Holy Cross, and University Medical Center Hospitals of the University of Utah. The technique provides the internist with valuable information during cardiac catheterization. It has been used for this more than 2,000 times. In addition, the system is being used to monitor patients in the intensive care units at the three hospitals. More than 200 patients have been monitored in this manner, the intrarterial catheter being left in place in some instances for as long as two weeks. With the catheter filled with heparin and flushed once or twice daily, clotting has not been a problem. No significant complications have occurred.16

The pressure-pulse method hitherto has been used only to a limited extent in the operating room; and recovery room, and so far has not been completely validated for special clinical conditions, such as during anesthesia. Recently the Division of Anesthesiology has started to use the technique in the operating rooms as a means of following the cardiodynamic reactions of seriously-ill patients undergoing routine surgery as well as those undergoing more formidable procedures such as open-heart surgery. It is especially useful in following the postoperative course of these cardiac surgery patients.

In addition, the technique is a versatile tool that lends itself well to basic and clinical research in anesthesiology. Two programs currently under way in our animal laboratories make use of this method of estimating cardiodynamics: exploration of the cardiovascular reactions to the gaseous anesthetic, enflurane (1,1,1,2-tetrafluoro-2-bromoethane); and study of the cardiovascular responses to rapid intravenous fluid administration during hypotension secondary to spinal or epidural anesthesia.

Summary

Rapid measurement of cardiovascular parameters, particularly cardiac output, under conditions that do not disturb the physiology of the subject and do not call into question the validity of results, has been the object of much work and experimentation. The method described here, based on analysis of the various characteristics of the central arterial pulse contour and programmed for on-line data analysis by a digital computer, enables the physician to receive a beat-to-beat estimation of his patient's stroke volume, heart rate, cardiac output, mean arterial pressure, and peripheral resistance in varied non-steady-state conditions with an absolute minimum of discomfort and disturbance of the subject's physiologic state.

Under a variety of physiologic conditions we have found this procedure to correlate well with more conventional means of measuring the output of the heart such as the direct Fick and indicator-dilution methods. The technique has become a versatile tool in basic and clinical research in anesthesiology, a valuable

---

**Fig. 3.** Comparisons between the pressure-pulse and the indicator-dilution techniques for estimating cardiac output in five dogs at various stages of hypotension under general anesthesia. Each dog is assigned a different symbol.
adjunct in the cardiovascular laboratory during cardiac catheterizations, and a means of monitoring patients in the operating room, recovery room, and intensive care unit.

Acknowledgment is made to Dr. Homer Warner, Professor and Chairman of the University of Utah Department of Biophysics and Bioengineering, for his advice and help in preparing this manuscript.

References


Surgery

TRANSURETHRAL RESECTION Three serious complications are avoidable and, at the present time, can be attributed to carelessness. Intravascular hemolysis can be prevented by use of an isotonic nonelectrolytic solution for irrigation. Hypervolemia and hyponatremia can be reduced by avoidance of overdistention of the bladder, use of arterial hypotension, and administration of mannitol. Intravascular explosion will not occur if all accumulated hydrogen and oxygen are released from the bladder frequently. (Crevey, C. D.: Reactions Peculiar to Transurethral Resection of the Prostate, Surg. Clin. N. Amer. 47: 1471 (Dec.) 1967.)