ABSTRACT
Large changes in stroke volume and peripheral vascular resistance were induced by varying the heart rate and by intra-aortically infusing acetylcholine or angiotensin II in six dogs with heart block and electromagnetic flowmeters chronically implanted around their ascending aortas. Changes in stroke volume, aortic and atrial pressures, and systemic resistance were monitored continuously for 3-6 hours under morphine-pentobarbital anesthesia. The characteristics of diastolic pressure decay at heart rates ranging from 60 beats/min to 200 beats/min and during transient periods of asystole were studied, especially with reference to the distortions caused by reflected pressure waves. The diastolic phase of pressure pulses recorded over a segment of the thoracic aorta several centimeters long centered about 4 cm cephalad to the dorsal insertion of the diaphragm could be closely approximated by a straight line on a semilogarithmic scale. Under the conditions of these experiments, changes in the slope of that line and of its reciprocal, the time constant, correlated well with concomitant variations in peripheral vascular resistance. This relationship appears to be of practical value for continuous monitoring of systemic resistance directly from the diastolic segments of pressure pulses recorded from the lower thoracic aorta.

KEY WORDS atrial-ventricular pacing dog vasoactive drugs peripheral vascular resistance central aortic pressure decay

The contour of the arterial pressure pulse varies dramatically during its transmission down the arterial tree, and the pressure decay during diastole is generally not a monotonic function of time (1-4). However, a relatively smooth diastolic pressure decay has been described for aortic pressure pulses recorded near the dorsal insertion of the diaphragm (5, 6); this observation has been confirmed repeatedly in our laboratory.

An initial objective of this study was to determine how uniformly an approximately monotonic diastolic decay of the aortic pressure pulse could be recorded from this particular site in the aorta in different dogs and during widely different hemodynamic conditions. Secondarily, a time-independent method of characterizing this pressure decay, presumably caused by drainage of blood from the large arteries to the periphery, was sought. If such a time-independent characterization could be established, it would allow extrapolation into the immediately preceding or subsequent systolic periods of the decrement in aortic pressure due to peripheral flow. If possible, this extrapolation would provide a means of "correcting" aortic pressures during systole for the drainage of blood from the great arteries during ventricular ejection. This increment in aortic pressure due to ventricular ejection might be directly related to individual values of stroke volume by, at worst, a small number of calibration factors or, at best, a single easily determined constant multiplier.

When pressure pulses were recorded from the above-mentioned specific aortic location in preliminary experiments, a plot of the logarithms of the aortic diastolic pressure decay values vs. time for any individual diastolic decay could consistently be approximated by a straight line. Furthermore, the slopes of these lines seemed to be closely related to the peripheral systemic resistance measured concurrently by independent techniques. The experiments were then redesigned to test the validity of this relationship and to find a computer-based
resistance directly from the diastolic segment of the aortic pressure pulse.

Methods

A cuff type of electromagnetic flowmeter (Carolina Medical Electronics) was implanted around the ascending aorta in six dogs (12-17 kg) 4-10 weeks before the experiments were performed. Complete atrioventricular block was produced at least 2 weeks before the experiments in three dogs, using the percutaneous technique of Williams and associates (7).

Anesthesia was produced with morphine sulfate (2.6 mg/kg, im) and sodium pentobarbital (15 mg/kg, iv). Additional sodium pentobarbital was given intravenously as needed during the experiment to maintain a light level of anesthesia. Respiration was controlled via auffed plastic endotracheal tube using an intermittent positive-pressure respirator (Bird Mark VII) with an average rate of 30 cycles/min and an inspiratory pressure of 8-10 cm H₂O. Respiration could be suspended temporarily during pressure recordings by opening the airway to ambient pressure.

In three of the experimental studies, acetylcholine (0.5 mg/ml) and angiotensin II (2.0 mg/ml) were employed as vasoactive substances. The infusion rate was varied in steps between 0.125 ml/min and 0.5 ml/min and maintained at a constant level during each step. The entire range of infusion rates was studied in each of these three dogs.

Catheters were introduced by percutaneous puncture of the external jugular veins with appropriately sized, internally polished needles (8). The intracardiac tips of two 6-F bipolar electrode catheters were positioned juxtaposed to the endocardium in the outflow tract of the right ventricle and the right atrium near the orifice of the superior vena cava. These electrodes were connected to electronically coupled pacemakers so that the heart rate and the temporal relationship of atrial-ventricular stimuli (3-msec negative-polarity square-wave pulses) could be controlled.

The tip of a third 6-F venous catheter was positioned in the main pulmonary artery. Three 5-F catheters were introduced into the aorta by percutaneous insertion into the femoral arteries. The tip of an 80-cm bird’s-eye Lehman catheter was positioned in the aortic arch just upstream from the origin of the brachiocephalic artery. This catheter was used for infusions of acetylcholine or angiotensin II to produce decreases or increases, respectively, in peripheral vascular resistance and resultant large changes in stroke volume (9). The tip of a 60-cm open-end Lehman catheter was positioned in the thoracic aorta a few centimeters cephalad to the dorsal insertion of the diaphragm; this catheter was used primarily for recording aortic pressure pulses via a strain-gauge manometer (Statham P23G). The tip of the third arterial catheter (60-cm open-end polyethylene) was positioned in the abdominal aorta, and the catheter was connected via a two-way stopcock to a densitometer (Waters 250A) for recording dilution curves of indocyanine green dye. All catheters were connected to the Lucite domes of strain-gauges (Statham P23D and P23G) via special low-compliance, threaded hypodermic stopcock adapters so that the catheters could be flushed with heparinized Ringer’s fluid external to the Lucite adapter dome. Use of these bypass flushing adapters avoided the relatively long-lasting shift of the base line that uniformly occurs when these gauges are flushed via the stopcock-Lucite dome assembly supplied by the manufacturer. The dynamic response characteristics of these catheter-strain gauge-manometer assemblies are adequate for recording circulatory pressure pulses in large mammals (10, 11).

A special low-noise electronic gating switch was incorporated in the input stage of the flowmeter electronics to avoid brief artificial deflections that have an amplitude large enough to cause a temporary partial blockage of the amplifier. The artifacts, which resulted from the relatively large stray currents generated at the flowmeter electrodes by the cardiac pacing pulses, would otherwise create temporary shifts in the base line of the flow-pulse data and make analysis difficult.

The electrocardiogram, the atrial and ventricular pacing stimuli, the aortic flow velocity, the multiple aortic, right atrial, right ventricular, pulmonary artery, and airway pressures, the amount and duration of injection of indocyanine green dye (1.25 mg/ml), the resulting arterial dye-dilution curves, and the binary-coded decimal signal for synchronization and search and retrieval purposes were recorded in parallel simultaneously on an analog tape recorder (Ampex FR 1200 14-channel FM) and a multichannel photokymographic d’Arsonval galvanometer assembly (12).

These analog data were converted on-line and in real-time to digital form at a rate of 200 samples/sec for each channel by a computer-controlled (CDC 3200) multiplexed (100,000 samples/sec) analog-to-digital converter. A 5-msec sample interval has been found adequate for accurate reproduction of the practically important information content of circulatory pressures and aortic flow pulses of large mammals; this interval was also consistent with reasonable computer time requirements for analyses of these data.

Each portion of the computer-based data analyses was carried out with specially written modular computer programs, which could be used in any desired order. The recordings on photosensitive paper were employed for hand and planimetric verification of the computer results.

The instantaneous slopes of the curves, i.e., the first derivative of the pressures (dP/dt), including magnitude and sign, were approximated by taking the differences between successive 5-msec values. These values were used as criteria for automated recognition of the various hemodynamically significant instants in time on the aortic pressure pulses. The beginning of the aortic systolic pressure rise, i.e., the beginning of ventricular ejection, was defined as a change in the sign of dP/dt from negative to positive. To minimize errors in the recognition of these important points, additional conditions were imposed: the beginning of systole, as it was recognized by the computer, should not occur more than 200 msec after the peak of the R wave of the electrocardiogram (ECG), and the onset of the systolic wave should be rapid and at least 75 msec in duration. Automated recognition of the onset of ventricular ejection, which included the various propagation delays associated with the measurement equipment, has proved to be reliable despite the large transient changes in stroke volume.
produced by ventricular extrasystoles at high heart rates. Reversals of the sign of the dP/dt values were also used for automated recognition of the peak systolic pressure, the incisura, the following dicrotic peak, and the onset of the diastolic decay.

The time constant that was used as a measure of the steepness of the individual diastolic decays was calculated for each curve by first sampling the diastolic pressures at 5-msec intervals from 30 msec after the lowest point of the incisura to 20 msec prior to the onset of the succeeding systole. The individual coordinate points \((t_i, P_i)\) were plotted on a semilogarithmic scale in which the new coordinate point values \((t_i, \log P_i)\) followed a nearly straight line with negative slope. The set of semilogarithmic points was approximated by the standard linear regression equation \(y = mx + b\), where \(m\) is the slope of the line and \(b\) is the ordinate intercept. The reciprocal of the slope with the sign disregarded was defined as the time constant for that diastolic delay. Sampling was not initiated until 30 msec after incisura and was terminated 20 msec prior to the onset of the following systole to minimize errors caused by aortic valve disturbances occurring near these two events. In certain instances, comparisons were made between values derived from the time constant and from the indicator-dilution measurements of cardiac output, with a consequent utilization of five to ten consecutive beats rather than individual pulses. In these cases, time

\[ \begin{align*}
\text{HEART RATE} & \quad \text{TIME CONSTANT} & \quad \text{CORRELATION COEFFICIENT} \\
160 & \quad 180 & \quad 1.21 & \quad 0.95 \\
150 & \quad 170 & \quad 1.29 & \quad 0.99 \\
140 & \quad 160 & \quad 1.38 & \quad 0.96 \\
130 & \quad 150 & \quad 1.50 & \quad 0.97 \\
120 & \quad 140 & \quad 1.33 & \quad 0.98 \\
110 & \quad 130 & \quad 1.27 & \quad 0.99 \\
100 & \quad 120 & \quad 1.33 & \quad 0.99 \\
90 & \quad 110 & \quad 1.39 & \quad 0.99 \\
80 & \quad 100 & \quad 1.38 & \quad 0.99 \\
70 & \quad 90 & \quad 1.42 & \quad 0.99 \\
60 & \quad 80 & \quad 1.45 & \quad 0.99 \\
50 & \quad 70 & \quad 1.50 & \quad 0.99 \\
40 & \quad 60 & \quad 1.65 & \quad 0.99 \\
30 & \quad 50 & \quad 1.95 & \quad 0.99 \\
20 & \quad 40 & \quad 1.69 & \quad 0.99 \\
10 & \quad 30 & \quad 1.95 & \quad 0.99 \\
0 & \quad 20 & \quad 1.99 & \quad 0.99 \\
\end{align*} \]

**FIGURE 2**

Influence of increasing heart rate on the contour and the time constant of diastolic pressure decays recorded at position \(E\) in the lower thoracic aorta (see Fig. 1). Note the maintenance of the apparent monotonic nature of diastolic segments of pressure pulses in spite of the large variation in heart rate. The time constants of corresponding aortic-diastolic pressure decays were determined from a semilogarithmic regression line as shown in Figure 3. The correlation coefficient is a measure of the closeness with which a sequence of sampled pressure values from the diastolic pressure decays can be represented by a straight line on a semilogarithmic scale.

![Diagram](image)

**FIGURE 1**

Effects of the position of the aortic catheter tip on the contour of diastolic pressure decay. A–H (left and right) correlate various pulse contours with corresponding positions of the catheter tip in different segments of the aorta. Broken lines indicate a pressure level of 100 mm Hg on each curve. Note the relatively smooth diastolic curve for position \(E\) of the catheter tip in contrast to the humps and troughs of curves recorded cephalad or caudal to this level.

constants for the individual pulses were averaged from the five to ten consecutive beats.

The analyses of the aortic flowmeter curves, including the recognition of the onset and the termination of the distal movement of blood in the ascending aorta and the determination of the maximal velocity (flow rate), were carried out in a manner similar to that used for the pressure pulse except that the first derivative of the flow \((dQ/dt)\) was used in place of \(dP/dt\). With the flowmeter located around the ascending aorta, the end-diastolic segment of the flow pulse was assumed to be a period of approximately zero flow.

Analyses of the dilution curves of indocyanine green dye for determinations of cardiac output by the Stewart-Hamilton method were carried out on-line and in real-time by the computer using the technique of Williams and co-workers (13). This technique provided compensation for recirculating indicator in the blood, thereby allowing repetitive determinations of cardiac output in rapid sequence. Average stroke volume was calculated by dividing the cardiac output by the heart rate in beats per minute. In addition, individual values of the stroke volume were computed from the areas under the flowmeter pulses after an in vivo calibration against the cardiac output from the indicator-dilution curve had been performed. A calibration constant to convert the flow-pulse area to stroke volume was thus obtained. The
flowmeter deflection was also calibrated in milliliters per second by comparing the cardiac output per minute from the dye-dilution curve with the flow-pulse area per minute of effective flow.

Results

Pressure pulses recorded from eight sites in the aorta of one dog during successive step withdrawals of the most centrally located catheter tip from just downstream from the aortic valve to the iliac bifurcation are shown in Figure 1. The positions of the catheter tips were determined from roentgenograms obtained after each step withdrawal. Simultaneous recordings from the aortic catheters whose tips were located at positions E and H indicated that the contours of the aortic pressure pulses at each of these two positions were constant throughout the period that these recordings were obtained.

Over a segment of the aorta several centimeters long centered at position E, the decay of the aortic pressure with time after the incisura appeared to be a monotonic function. The apparently monotonic nature of the diastolic decay was maintained over a range of heart rates from 46 beats/min to 180 beats/min (Fig. 2). Although the contours of both the systolic and the diastolic segments of aortic pressure pulses were very different at different sites in the aorta, under steady-state conditions, the contour at any given site was reasonably constant over long periods. The differing physical characteristics of the catheters did not affect the ability to record pressure decays with simple monotonic slopes in the region near position E. Furthermore, although the contours of the systolic segments of the aortic pulses varied considerably at all sites under different hemodynamic conditions, the monotonic nature of the diastolic pressure decay recorded about 2-4 cm cephalad to the dorsal insertion of the diaphragm was essentially unchanged (Fig. 3).

Attempts to represent the diastolic decay of aortic pressure at this particular site in the aorta by a characteristic time constant derived from plots of log P vs. time were successful in all six dogs at all heart rates and over the range of hemodynamic conditions studied. The wide range of hemodynamic states induced in the six dogs is shown in Table 1 and for dog 4 in Figure 4. The only values included in Figure 4 and Table 1 were those derived from the first ten heart beats immediately following the successive injections of indocyanine green dye; the arterial dye-dilution curves were used to calculate the multiple cardiac output values plotted in Figure 4. Four-, five-, and ninefold changes

Heart Block Dog, 17 kg, Morphine - Pentobarbital Anesthesia

<table>
<thead>
<tr>
<th>INTRA-AORTIC: ANGIOTENSIN (1.0 µg/min)</th>
<th>ACETYLCHOLINE (0.25 mg/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AORTA (mm Hg)</td>
<td></td>
</tr>
<tr>
<td>150</td>
<td>125</td>
</tr>
<tr>
<td>100</td>
<td>75</td>
</tr>
<tr>
<td>200</td>
<td>7.3</td>
</tr>
<tr>
<td>FLOW (ml/sec)</td>
<td>0.5 sec</td>
</tr>
<tr>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>ECG</td>
<td></td>
</tr>
<tr>
<td>Stroke Volume (ml)</td>
<td>10.5</td>
</tr>
<tr>
<td>Peripheral Resistance (mm Hg/ml/sec)</td>
<td>3.1</td>
</tr>
<tr>
<td>200</td>
<td></td>
</tr>
</tbody>
</table>

FIGURE 3

Maintenance of the apparent monotonic nature of diastolic segments of aortic pressure pulses during infusions of angiotensin II and acetylcholine. Heart rates of 120 beats/min were identical, but differences in mean aortic pressures of about 150 mm Hg and 100 mm Hg, stroke volumes of 10.5 ml and 18.0 ml, and peripheral vascular resistances of 7.3 mm Hg/ml/sec⁻¹ and 3.1 mm Hg/ml/sec⁻¹, respectively, under the two conditions were large. In spite of these alterations, diastolic pressure decays appear to be monotonic.
TABLE 1

Range of Hemodynamic Parameters Induced in Six Dogs by Intra-Aortic Infusions of Acetylcholine and Angiotensin II and by Cardiac Pacing (Morphine-Pentobarbital Anesthesia)

<table>
<thead>
<tr>
<th>Dog</th>
<th>Weightobservations (kg)</th>
<th>Duration of observations (hours)</th>
<th>No. of dilution curves*</th>
<th>Cardiac output* (liters/min)</th>
<th>Heart rate† (beats/min)</th>
<th>Maximal aortic flow (ml/sec)</th>
<th>Mean aortic pressure (mm Hg)</th>
<th>Aortic pulse pressure (mm Hg)</th>
<th>Systemic vascular resistance (mm Hg/ml sec⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>16</td>
<td>6.165</td>
<td>13</td>
<td>1.70-2.75</td>
<td>60-186</td>
<td>125-240</td>
<td>112-132</td>
<td>25-45</td>
<td>2.0-4.6</td>
</tr>
<tr>
<td>2</td>
<td>15</td>
<td>3.33</td>
<td>16</td>
<td>1.68-3.20</td>
<td>56-180</td>
<td>175-270</td>
<td>88-160</td>
<td>20-65</td>
<td>2.0-5.0</td>
</tr>
<tr>
<td>3†</td>
<td>13</td>
<td>3</td>
<td>6</td>
<td>0.80-3.45</td>
<td>30-160</td>
<td>120-240</td>
<td>86-140</td>
<td>30-55</td>
<td>1.6-7.5</td>
</tr>
<tr>
<td>4‡</td>
<td>14</td>
<td>4.75</td>
<td>28</td>
<td>1.30-6.00</td>
<td>45-190</td>
<td>155-460</td>
<td>88-145</td>
<td>20-60</td>
<td>0.7-6.4</td>
</tr>
<tr>
<td>5‡</td>
<td>12</td>
<td>3</td>
<td>22</td>
<td>1.20-4.00</td>
<td>28-180</td>
<td>95-270</td>
<td>80-150</td>
<td>18-52</td>
<td>1.2-7.1</td>
</tr>
<tr>
<td>6</td>
<td>17</td>
<td>3.25</td>
<td>12</td>
<td>1.30-3.25</td>
<td>52-157</td>
<td>97-248</td>
<td>82-108</td>
<td>20-30</td>
<td>1.8-4.7</td>
</tr>
</tbody>
</table>

* Range of cardiac output values determined by arterial dilution curves of indocyanine green dye. Number of determinations is given for each dog.
† Heart rates, pressures, and resistance values based on first ten beats after each injection of indocyanine green dye into the pulmonary artery.
‡ Dogs with chronic atrioventricular block.

Figure 4

Example of hemodynamic changes induced during 4.75 hours in an anesthetized dog that had chronic heart block. Note the large variations in values of individual parameters that were induced by infusions of acetylcholine or angiotensin II into the aortic arch while heart was paced electrically at various rates and various atrioventricular stimulus intervals. Wide variations in other parameters resulted from alterations in electrical pacing, infusions of vasoactive substances, or both. Durations of continuous infusions are indicated.

Figure 5 (left) shows individual aortic pressure pulses recorded from a site approximately 4 cm cephalad to the dorsal attachment of the diaphragm during intra-aortic infusions of angiotensin II and acetylcholine. The respective semilogarithmic plots of the diastolic segments of these two pressure pulses are shown in Figure 5 (right). The straight lines through each set of values are the calculated regression lines for the respective data sets and indicate that the diastolic pressure decays for these two pulses can be represented with reasonable accuracy by their respective slopes. The slope of the decay of aortic pressure during diastole recorded during infusion of acetylcholine was about twice as steep as that recorded during infusion of angiotensin. The corresponding values for the time constants of these diastolic decays were 2.52 seconds and 1.19 seconds, respectively. The ratio was 2.12:1 compared with the ratio of 2.36:1 for the peripheral resistance values derived from the ratios of pressure to cardiac output of 7.3 mm Hg/ml sec⁻¹ and 3.1 mm Hg/ml sec⁻¹, respectively, that were measured concomitantly with the recording of these two pressure pulses.

The time constant that characterizes the slope of the diastolic decay remained essentially constant in heart rate, cardiac output, and peripheral vascular resistance were observed while aortic systolic pressure, mean pressure, pulse pressure, and diastolic pressure ranged from 110 to 160 mm Hg, 88 to 145 mm Hg, 20 to 60 mm Hg, and 55 to 130 mm Hg, respectively. Similar or even greater variations were observed in the other five dogs (Table 1).
Demonstration of the semilogarithmic relationship between aortic pressure and time during the diastolic segment of pressure pulses recorded from a caudal site in the thoracic aorta. **Left:** Two arterial pressure pulses recorded during infusions of angiotensin II and acetylcholine into the arch of the aorta. **Right:** Semilogarithmic plots of pressure values sampled at every 1-mm Hg decrement in pressure during diastolic segments of aortic pressure pulses plotted against an expanded time scale on the x-axis. The heavy lines through the sampled points are the linear regression lines computed for the two sets of values. The decrease in pressure from the dicrotic notch to end-diastole during angiotensin infusion was only 43%, on a logarithmic scale, of the decrease in pressure during a similar diastolic period during infusion of acetylcholine. Conversely, the ratio of values of the aortic-diastolic pressure decay time constant \( T \) during acetylcholine infusion to that during angiotensin infusion was 0.47. This value is closely similar to the ratio, 0.42, of the peripheral vascular resistance values of 3.1 mm Hg/ml sec\(^{-1}\) and 7.3 mm Hg/ml sec\(^{-1}\) measured concomitantly with recording of these pressure pulses.

Representation of behavior of aortic-diastolic pressure decay during and around an asystolic period of 8.5 seconds. Just below the original pressure tracings, the straight lines drawn at oblique angles correspond to regression lines of individual diastolic pressure decays plotted as semilogarithmic functions. The ordinate of the middle record represents logarithms of the diastolic pressures. The diastolic values were scaled for each beat so that the log of the maximal pressure at incisura was 100%. Individual diastolic decays were extrapolated to 37% of their maximal ordinate values to allow direct reading of the time constant for each curve from the abscissa. Duration of the asystolic period is indicated by the tick marks at 1-second intervals on the horizontal time scale. The series of diverging lines represents calculated diastolic regressions for the initial 1.5 seconds and for each consecutive second of the asystolic period. During the initial 1.5 seconds after onset of asystole, the calculated value of the time constant was similar to values of preceding diastolic curves from the normally rhythmic portion of the record, as demonstrated by the parallel courses of the regression lines. During the following 1-second period of long diastole, the time constant increased to 5 seconds. The slope of diastolic pressure decay decreased progressively up to the termination of the asystolic phase; this decrease was followed by a progressive increase back to the control value (as indicated by parallelism between the first and the last regression lines) over 13–15 heart beats after resumption of normal rhythm. All beats prior to asystole were controlled by electrical pacing. The first three beats after prolonged diastole were spontaneous extrasystoles; thereafter, electrical pacing was reinitiated.
under steady-state conditions in all six dogs. However, changes in arterial blood pressure that lasted more than 1–1.5 seconds produced progressive changes in the slope of the diastolic decay curve. This effect is illustrated in Figure 6, based on recordings from a dog with chronic heart block in which an 8.5-second period of asystole was produced by sudden stoppage of the atrial and the ventricular pacing stimuli.

Although the decay curve of aortic pressure was smooth throughout the long diastolic period, there was a progressive decrease in the slope (increase in the time constant) of the semilogarithmic decay beginning about 1.5 seconds after the onset of the asystolic period. These changes are depicted graphically in Figure 6 in which semilogarithmic plots (regression lines of the time, log P coordinates) of the diastolic pressure decays are positioned below their respective pressure pulses. The decays during each successive second after the initial 1.5 seconds of the 8.5-second period of asystole are plotted sequentially with their origins superimposed at the incisura of the last control systole. The regression line from the initial 1.5 seconds of asystole and each line for the seven successive 1-second increments were extended over a pressure range of 100 mm Hg to 37 mm Hg so that their durations on the horizontal time scale were automatically equal to the time constants (reciprocal of the slope) of their decays. The time constants of the five steady-state control pulses preceding the asystolic period were not significantly different. After the initial 1.5 seconds of asystole, the values increased progressively from about 1.5 seconds to 9.5 seconds for the last second of the 8.5-second asystolic period. The time constant for the decay of each successive pulse following the asystolic period then decreased progressively to the control value 13 beats (12 seconds) later.

Transient large changes in stroke volume (SV) and consequent changes in aortic pressure (not longer than 1–2 seconds) did not cause large
changes in the time constant ($\tau$) of the successive pressure pulses, e.g., in Figure 7, $SV_{min}/SV_{max} = 3.1/23.3$ and $t_{min}/t_{max} = 1.7/2.1$.

The progressive increases in the time constant of the diastolic pressure decay during a long period of asystole (Fig. 6) and the increases and the decreases uniformly observed during aortic infusions of angiotensin II and acetylcholine, respectively, indicate that the magnitude of the time constant might be a function of the peripheral vascular resistance. The parallel appearance of plots of simultaneously determined time constants and peripheral systemic resistances vs. time during 3-6 hours of observation in the six dogs supports this finding, as illustrated by the data from one dog (Fig. 8). In spite of seven- to eightfold ranges of time constants and systemic resistances that were induced in this dog during the 4.75 hours of observation, the two sets of values maintained a nearly parallel (approximately linear) relationship. This nearly linear relationship between the time constants of the diastolic decay of the pressure pulses and the peripheral resistance values measured simultaneously in each dog studied under similar conditions is illustrated in Figure 9. Five of the six regression lines calculated for the coordinate pairs of time constant and peripheral resistance values yielded correlation coefficients greater than 0.90. Extrapolation of the regression lines yielded y-intercepts with nearly zero values for four dogs and negative values for two dogs. The existence of a linear relationship between time constants and peripheral resistances was statistically significant ($P < 0.01, 0.005$, and 0.001) in all dogs.

The accuracy of determinations of the regression line of peripheral resistance and time constant values should increase with the number of observations, particularly if the range of values is large. Because the number of recordings of simultaneous aortic flow pulses and aortic and right atrial pressures was much greater than the number of indocyanine green dye-dilution curves obtained during the 3-6 hours of observation in the six dogs, it was possible, using the multiple cardiac output values calculated from the flow pulses recorded by the aortic flowmeter, to obtain many more simultaneous peripheral resistance and time constant values.

The average values measured from ten consecutive cardiac cycles were used for each pair of
coordinate values. To avoid possible transient effects on peripheral resistance during the period of measurement, groups of ten beats containing a transient diastolic period of greater than 1.5 seconds were not used. An in vivo calibration factor based on the cardiac output value determined from the initial dye-dilution curve recorded at the beginning of the 3-6 hours of observation was used to convert the flowmeter pulse areas to stroke volumes. Plots of the 64-162 coordinate values obtained for each of the dogs are shown in Figure 10.

When the extrapolated regression line intersected the y-axis close to zero, the relationship between the time constant (τ) and the peripheral resistance (R) was approximated by the expression

\[ R = K \cdot \tau \]

This expression should have practical value under some conditions as a method for estimating changes in systemic peripheral vascular resistance from aortic pressure pulses alone. This possibility was tested further by using the peripheral resistance values determined from the first simultaneous recording of aortic pressure pulses and the determination of cardiac output by the indicator-dilution technique to calculate the value of K in the relationship \( R = K \cdot \tau \).

This equation and the calculated K value were then used to calculate peripheral resistance values for each of the subsequent recordings of ten or more successive aortic pressure pulses for which simultaneous recordings of aortic flow pulses were obtained.

\[ N \times 147 \]

\[ Y = 1.99X + 0.58 \]

\[ SE = 0.39 \]

\[ P < 0.001 \]

\[ +0.56 \]

\[ SE = 0.39 \]

\[ P < 0.39 \]

\[ r = 0.83 \]

\[ P < 0.001 \]

\[ Y \times 1.99X + 0.58 \]

\[ SE = 0.39 \]

\[ P < 0.001 \]

\[ +0.56 \]

\[ SE = 0.39 \]

\[ P < 0.001 \]

\[ Y \times 1.99X + 0.58 \]

\[ SE = 0.39 \]

\[ P < 0.001 \]

\[ +0.56 \]

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\[ Y \times 1.99X + 0.58 \]

\[ SE = 0.39 \]

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\[ +0.56 \]

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\[ Y \times 1.99X + 0.58 \]

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\[ +0.56 \]

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\[ P < 0.001 \]

\[ Y \times 1.99X + 0.58 \]

\[ SE = 0.39 \]

\[ P < 0.001 \]

\[ +0.56 \]

\[ SE = 0.39 \]

\[ P < 0.001 \]

\[ Y \times 1.99X + 0.58 \]

\[ SE = 0.39 \]

\[ P < 0.001 \]

Demonstration of a linear relationship between simultaneously determined peripheral vascular resistance values and time constants of diastolic pressure decays in caudal thoracic aortas of six dogs under morphine-pentobarbital anesthesia. Aortic flow was determined from groups of ten flowmeter pulses, enabling calculation of a greater number of peripheral resistance values than could be presented in Figure 9. The y-intercepts of the regression lines approach zero in all six dogs (range -0.11 to +0.58). Broken lines on either side of each regression line represent the 96% of the estimate (range ±0.26 to ±0.83).
Demonstration of agreement between peripheral resistance, calculated from mean aortic pressure and aortic electromagnetic flow pulse (RFM), and peripheral resistance (R), estimated from time constants (τ) of diastolic pressure decays of same heartbeats via the formula $R = K \cdot \tau$. Aortic pressures were recorded from catheters placed in the caudal thoracic aortas of six dogs under morphine-pentobarbital anesthesia. The conversion factor $K = RFM/\tau$ was calculated once for each dog after the first determination of RFM from a group of ten consecutive simultaneously recorded pairs of aortic flow and pressure pulses. Lines of equality, i.e., the broken straight lines through the origins with a slope of one, are included in each section of the figure.

The proximity of the sets of coordinate points to a line of equality, i.e., to a straight line through the origin with a slope of one, for each dog supports the assumption that the relationship between the diastolic decay time constant and the systemic resistance might be reasonably approximated by the simplified expression $R = K \cdot \tau$.

**Discussion**

It is interesting that the empirically observed, approximately linear relationship between the time constants of the diastolic decay of aortic pressure pulses recorded from a caudal segment of the thoracic aorta and the simultaneously determined resistance values measured by independent techniques pertained over a wide range of hemodynamic conditions. This finding implies that changes in the capacitive component contributed by the aorta and its branches, which would be expected to occur under the conditions of these experiments, did not significantly influence the numerical value of the time constant.

Without regard to possible explanations for the observed relationship between the time constants and the peripheral resistances, this finding could also have practical clinical applications if it were demonstrated in humans that the time constants of the diastolic decay of aortic pressure pulses recorded from a particular segment of the aorta were linearly related to the systemic resistance. Since arterial pressure pulses can be recorded continuously over long time periods with relative ease (14), the relationship $R = K \cdot \tau + b$ could be used as a basis for indirect monitoring of changes in peripheral vascular resistance in critically ill patients. A simultaneous determination of cardiac output pre-
sumably would allow expression of the estimated resistance values in absolute units, particularly if the y-intercept (b) was not significantly different from zero.

The demonstration that the decay of pressure in a particular segment of the aorta cephalad to the dorsal insertion of the diaphragm can be represented accurately by a single time constant value provides the further possibility of correcting aortic pressure for the effect of blood flow to the periphery during ventricular ejection. This capability is being used to improve the accuracy of measurement of beat-to-beat changes in stroke volume from aortic pressure pulses.

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