A Technic of Vascular Catheterization with Small Plastic Catheters
Its Utilization to Measure the Arterial Pulse Wave Velocity in Man

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A method of vascular catheterization is presented in which small polyvinyl catheters are introduced into peripheral vessels through 18 to 21 gage needles and then advanced into the central vascular bed. This technic has been utilized in the study of hemodynamic events occurring in the central arterial vessels in man. The results obtained from 31 arterial catheterizations done in 21 subjects are reported. Utilizing this technic, it has been impossible to catheterize the pulmonary artery in man. However, the method has proved useful in the study of right atrial and central venous pressure changes.

Catheterization procedures used to study the vascular dynamics in man necessitate exposure of a vessel to permit introduction of the large caliper catheters currently in use. The development of the Lilly capacitance manometer has made possible the recording of peripheral intra-arterial pressures with small plastic catheters.

Central vascular pressures can be recorded through similar catheters which are longer but of sufficiently small caliber that they may be inserted into the vascular system through an 18 to 20 gage needle. This paper reports the use of this technic for venous and arterial catheterization and the results obtained during catheterization of the central and peripheral arteries in man.

Materials and Methods

Polyvinyl tubing, plain or impregnated with barium sulfate for radiopacity, is treated with ether or heat to make catheters with properties suitable for manipulation and for recording pressures. The manometric system used is identical with that described previously. Blood samples can be drawn at rates up to 4 cc. per minute and have been analyzed by a micromethod described by Deering. Catheters are inserted through needles of 18 to 21 gage with walls thinner than those of standard gage needles. For catheterization of the aorta, the brachial or femoral artery is punctured with a 19 gage needle and the catheter passed under fluoroscopic guidance to the desired site. For venous catheterization the same procedure is followed, using the external jugular, internal jugular, basilic, or femoral veins as the entrance site for the catheter. Arterial and venous pressure curves are recorded simultaneously with lead II of the electrocardiogram. To calculate pulse wave velocity the catheter is moved through a measured distance in the vessel and this distance is divided by the difference in time of onset of the pulse at the two sites in relation to the Q wave of the electrocardiogram. The start of the arterial pulse is taken as that point at which the first detectable rise in pressure is noted. Recording paper speed was 125 mm. per second, allowing measurements to be made accurately to ±0.001 second. Subjects were fasting six hours and supine. Figure 1 is an example of the central aortic pulse contour recorded just distal to the aortic valve in a normal subject.

Results

Forty-one aortic catheterizations have been performed in 25 subjects. The results reported here cover 31 studies in 21 individuals. Subjects have ranged in age from a 5 week old infant to a 60 year old man, and may be
Fig. 1. A central aortic pulse recorded just distal to the aortic valve and a simultaneous electrocardiogram (lead II). Vertical time lines = 0.2 second.

TABLE 1.—Average Pulse Wave Velocities (Meters per Second) and Their Ranges Obtained in Central and Peripheral Vessels

<table>
<thead>
<tr>
<th>Group</th>
<th>Age Range</th>
<th>No. Deter</th>
<th>Average PWV</th>
<th>Range PWV</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>20-24 yrs</td>
<td>1</td>
<td>4.2</td>
<td>3.8-6.3</td>
</tr>
<tr>
<td>II</td>
<td>25-34 yrs</td>
<td>2</td>
<td>5.6</td>
<td>4.7-5.9</td>
</tr>
<tr>
<td>III</td>
<td>35-44 yrs</td>
<td>1</td>
<td>5.0</td>
<td>4.2-5.9</td>
</tr>
</tbody>
</table>

- Group I, 20-24 years, 10 individuals
- Group II, 25-34 years, 4 individuals
- Group III, 35-44 years, 2 individuals

Recorded as proximal end of brachial artery only.

The average pulse wave velocities and their ranges in the various arterial segments. The overall averages of 16 normal subjects between 20 and 40 years of age show that the pulse wave velocity in the ascending and descending aorta is approximately 5 meters per second. The pulse wave velocities in the subclavian and axillary arteries as well as in the abdominal aorta are somewhat slower, being

grouped as follows: group I, 10 healthy men, 20 to 24 years old; group II, four healthy men, 25 to 34 years old; group III, two healthy men, 35 and 44 years old; and group IV, a heterogenous group, including two males with thrombosis of the lower segment of the abdominal aorta, an infant and an adult female with aortic stenosis, and a male with an anomalous right subclavian artery.

Table 1 shows the average pulse wave velocities and their ranges in the various peripheral segments. The average pulse wave velocities in the ascending and descending aorta is approximately 5 meters per second. The pulse wave velocities in the subclavian and axillary arteries as well as in the abdominal aorta are somewhat slower, being

*Recorded in proximal end of brachial artery only.*
4.2 meters per second and 4.6 meters per second, respectively. There is a marked increase in the velocity of the pulse wave in the brachial and iliac arteries where it averages 8.2 meters per second, and 8.4 meters per second. The over-all pulse wave velocity from the aortic valve to the femoral artery is 5.3 meters per second, and from the subclavian to brachial artery 5.5 meters per second. In group IV the infant’s pulse wave velocity is somewhat slower, whereas the 69 year old patient with arteriosclerosis has the fastest pulse wave velocity found in the brachial artery. The findings in the adult female with aortic stenosis are within the normal range. Average figures for each group show a gradual rise in the pulse wave velocity with increasing age.

Figure 2 is a plot of the velocities of consecutive 10 cm. arterial segments for 13 of the 16 normal individuals. Three cases are not included because of incomplete data. All 13 individuals show a minimum pulse wave velocity in the region of the diaphragm, in 11 instances within 5 cm. of the diaphragm, and in two cases 12 cm. below the diaphragm. Nine of 11 cases show a decrease in the pulse wave velocity in the axillary or subclavian arteries when compared with its speed in the descending aorta.

Table 2 shows the time difference between the Q wave of lead II of the electrocardiogram and the onset of the pulse in various parts of the arterial system. The first detectable rise in pressure at the aortic valves occurs on the average .085 second after the Q wave. The Q to brachial time averages .167 second and the Q to femoral time averages .205 second. Both show an inverse relation to age.

In most cases the sensitivity of the manometer was increased to permit magnification of the pulse contours, thus preventing measurement of diastolic pressures. In three individuals the systolic, diastolic, and mean pressures were recorded accurately (table 3). There is a general increase in the pulse pressure as the catheter

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**Table 2.—Time Relations in Seconds between the Q Wave of Lead II of the Electrocardiogram and the Onset of the Pulse at Different Sites in the Arterial Tree**

<table>
<thead>
<tr>
<th>Group I</th>
<th>Q-Brachial</th>
<th>Q-Femoral</th>
<th>Q-Subclavian</th>
<th>Q-Carotid</th>
<th>Q-Aortic Valve</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. Determinations</td>
<td>8</td>
<td>9</td>
<td>6</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>Average</td>
<td>.173</td>
<td>.211</td>
<td>.119</td>
<td>.112</td>
<td>.071</td>
</tr>
<tr>
<td>Range</td>
<td>.148-.192</td>
<td>.190-.237</td>
<td>.102-.141</td>
<td>.089-.130</td>
<td></td>
</tr>
<tr>
<td>Group II</td>
<td>2</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>No. Determinations</td>
<td>2</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>.089</td>
</tr>
<tr>
<td>Average</td>
<td>.156</td>
<td>.201</td>
<td>.116</td>
<td></td>
<td>.077-.100</td>
</tr>
<tr>
<td>Range</td>
<td>.141-.170</td>
<td>.183-.223</td>
<td>.101-.132</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Group III</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>No. Determinations</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>.092</td>
</tr>
<tr>
<td>Average</td>
<td>.146</td>
<td>.189</td>
<td>.109</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Range</td>
<td>.183-.195</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Totals of Above 3 Groups</td>
<td>11</td>
<td>15</td>
<td>9</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>No. Determinations</td>
<td>.167</td>
<td>.205</td>
<td>.117</td>
<td>.112</td>
<td>.085</td>
</tr>
<tr>
<td>Average</td>
<td>.141-.192</td>
<td>.183-.237</td>
<td>.102-.141</td>
<td>.089-.130</td>
<td>.071-.100</td>
</tr>
</tbody>
</table>

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**Fig. 2.** Graph of the aortic pulse wave velocities in consecutive 10 cm. segments for 13 of the 16 normal individuals.
progresses toward the periphery with no significant change in the mean pressure. In two instances the increased pulse pressure was primarily due to a rise in systolic pressure. In one instance the fall in diastolic pressure was equal to the rise in systolic pressure.

Table 3.—Systolic (S), Diastolic (D), Mean (M) and Pulse (P) Pressures Obtained in the Aortic and Iliac Arteries of Three Normal Individuals

<table>
<thead>
<tr>
<th></th>
<th>I</th>
<th>II</th>
<th>III</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M</td>
<td>S</td>
<td>D</td>
</tr>
<tr>
<td>Ascending...</td>
<td>77</td>
<td>84</td>
<td>68</td>
</tr>
<tr>
<td>Descending...</td>
<td>75</td>
<td>84</td>
<td>63</td>
</tr>
<tr>
<td>Abdominal...</td>
<td>76</td>
<td>99</td>
<td>64</td>
</tr>
<tr>
<td>Femoral...</td>
<td>76</td>
<td>103</td>
<td>62</td>
</tr>
<tr>
<td>Over-all...</td>
<td>-1</td>
<td>+19</td>
<td>-6</td>
</tr>
</tbody>
</table>

Discussion

The use of catheters with small diameters which may be inserted into an artery or vein through a needle eliminates exposure of the vessel and minimizes trauma to the vessel and subject. In addition the small space occupied by the catheter within the lumen of the vein or artery results in less interference with the dynamics of flow in the vessel. Valves, irregular cardiac chambers, and the acute angulation required for the catheter to enter the pulmonary artery are inherent sources of risk in this as in any cardiac catheterization. In a series of 40 dogs in whom right heart catheterization was done, 25 per cent showed small subendothelial hemorrhages in the right auricle or right ventricle. In one instance a mural thrombus was present in the right auricle, and on one occasion the catheter looped itself around a papillary muscle with its tip impinged under a leaflet of the tricuspid valve, making removal impossible. Fifty per cent of the dogs in whom the left ventricle was catheterized showed small ecchymotic areas on the leaflets of the aortic valves.

It had been hoped that this technic might be utilized to catheterize the pulmonary artery in man. Experienced gained during 20 venous catheterizations has shown that this is not feasible due to the difficulty encountered in manipulating a small catheter within the right heart. The technic has proved ideal, however, for the study of right auricular and central venous pressure curves in man. The simplicity of the procedure as well as the lack of trauma to the patient has permitted the repeated performance of right auricular catheterization in the same individual, utilizing one vein as the entrance site of the catheter.

The first three human subjects for aortic catheterization developed pain in the distal phalanges of the catheterized arm. Pain occurred three to four hours after completion of the procedure, reaching maximum intensity in eight hours and gradually disappearing over a two week period. Limiting the procedure to one hour and modifying the catheter production technic has lessened the frequency and severity of the symptoms. Except for occasional small hematomas, the only other complication noted was in the 69 year old man with arteriosclerosis and thrombosis of the terminal aorta. Five minutes following removal of the brachial catheter the brachial and radial pulsations were not present, the hand blanched, and the subject complained of pain and tingling in his hand. The pulsations returned to normal one hour later without treatment and no subsequent symptoms were noted.

Methods of determining pulse wave velocity used by Bazett, Sands, Hallock and Haynes necessitated the estimation of the length of the arterial segment. It was impossible with their technics to measure the velocity of the pulse in localized segments of the aorta or other central vessels. The method utilized in this paper permits the measurement of pulse wave velocities over small segments of the aorta, for the arterial segment is measured by the distance the catheter is withdrawn. This relation holds except for the arch of the aorta.
where it has been assumed that the catheter follows the mean curvature.

The errors inherent in the method lie in the degree of accuracy with which the point of onset of the pulse curve can be estimated. With high paper speed, permitting the measurement of small time intervals, the onset of arterial systole is gradual. To minimize this source of error the time delay between the Q wave and the onset of the arterial pulse was averaged for five consecutive beats at each resting site of the catheter. In addition, mensurations in each case were made solely by one of the authors. Although the velocity of the pulse wave may be measured in a small segment of an artery, the possible error in the final determination increases markedly the shorter the segment and the faster the transmission time. Errors in measurements of the pulse curves of plus or minus .001 second allow an error of plus or minus 20 per cent in the final calculated pulse wave velocity in an iliac segment 10 cm. long. In central vessels, where the pulse wave velocity is slower, errors in measurements of the pulse curves may account for an error of plus or minus 10 per cent in the final calculated pulse wave velocity. In an effort to decrease the significance of these sources of errors, mean values for pulse wave velocities over the longest possible segments are reported in this paper.

The differences between the mean pulse wave velocity in the aorta and the mean velocities of the pulse in the brachial and iliac arteries are greater than 3 standard errors of the difference of the means and therefore highly significant. Pulse wave velocities of 8.2 meters per second and 8.4 meters per second in the brachial and iliac arteries, respectively, are slightly lower than figures reported by others of the pulse wave velocity from the femoral to the dorsalis pedis arteries and from the brachial to the radial arteries. The constant deceleration of the pulse wave velocity in the region of the diaphragm results in slightly lower mean values for the pulse wave velocity of the abdominal aorta as compared with that of the thoracic aorta. The difference between the means of the velocities of the pulse in these two areas is not significantly different but might become so were the series of cases larger.

These results indicate that a marked increase in the pulse wave velocity does not occur until the pulse reaches the brachial or iliac vessels and that the pulse wave velocity increases only slightly from the brachial and iliac vessels to the radial and dorsalis pedis arteries respectively. At the level of the diaphragm and in the subclavian artery there is a deceleration of the pulse wave velocity. This deceleration can be explained on the basis of (1) changes in regional distensibility of the vessels due to (a) intrinsic regional structural variations in the vessels, (b) difference in the extrinsic pressure exerted by surrounding tissues or organs, (c) changes from subatmospheric to atmospheric pressure; or, (2) changes near the ostia of large vessels such as the celiac and renal arteries.

In five instances the catheter was passed directly to the aortic valve permitting calculation of the pulse wave velocity over the entire aorta. The Q to aortic time averaged .085 second which is similar to the Q to pulmonary artery time reported by Coblentz.10

**Conclusions**

1. The use of small caliber catheters inserted through 18 to 21 gage needles for aortic and right heart catheterizations in man is reported. It has been impossible to catheterize the pulmonary artery in man by this method. However, the technic has proved useful in the study of right auricular and central venous pressure variations.

2. The pulse wave velocity is approximately 5 meters per second in the human aorta and 8 meters per second in the brachial and iliac arteries.

3. There is a deceleration of the pulse wave in the vicinity of the diaphragm and the subclavian artery.

4. The onset of left ventricular ejection follows the Q wave of lead II of the electrocardiogram by an average of .085 second.

5. The time from Q to brachial pulse averages .167 second; from Q to femoral pulse averages .211 second.

6. There is an increase in the pulse pressure from the aortic valve to the femoral artery.
A TECHNIC OF VASCULAR CATHETERIZATION

The mean pressures over this segment shows no significant change.

ACKNOWLEDGMENTS

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