Mechanics of the Human Common Carotid Artery in Vivo

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A knowledge of the motions and physical properties of the large arteries during life is important in the study of the circulation. For example, the nature of any fluid movement is markedly influenced by its boundary conditions. Thus, any acceptable mathematical treatment of pulsatile blood flow must include a formulation of the vascular wall properties. These mechanical properties must be evaluated at several sites along the arterial tree since the vessels change in both size and composition throughout their length. Furthermore, because the mechanical properties of vessels are usually altered by excision, this study is best done in vivo. Peterson et al., Bergel, and Patel et al. studied the relation between intravascular pressure and vessel diameter in the dog aorta and its major branches. These workers noted a progressive increase in stiffness along the arterial tree from the ascending aorta to the larger branches. A similar evaluation of the great arterial vessels in man would be valuable, but it is not technically possible at present. The relation between lateral intravascular pressure and vessel diameter has been studied in man. However, no data are available on the motions and mechanical properties of the large branches of the aorta. The purpose of this study was to evaluate the relation between lateral intravascular pressure, vessel diameter, and vessel length in the common carotid artery of the human subject during life.

Methods

The measurements were obtained from thirteen male patients during surgical exposure of the common carotid artery for clinical conditions listed under "Diagnosis" in table 1. In those patients with an intracranial aneurysm, the common carotid artery was exposed in order to place a Crutchfield clamp around this vessel so that it could be gradually occluded. In patients with a tumor (histologically classified as a glioblastoma multiforme), the common carotid artery was exposed in order to infuse an antitumor drug directly into the internal carotid artery. An endarterectomy for occlusive arterial disease of the carotid bifurcation was done on one patient, and another patient was explored in order to excise the stellate ganglion. Each patient was given 100 mg secobarbital, 75 mg meperidine, and 0.6 mg atropine as premedication approximately one hour before the operation. Surgical procedures were performed under local anesthesia (1% lidocaine) in two cases, and under general anesthesia in the remainder. The general anesthetic agent consisted of a mixture of nitrous oxide (49.5%), oxygen (50%), and halothane (0.5%). The common carotid artery was studied approximately three cm proximal to its bifurcation into the internal and external carotid arteries. Surgical exposure of the vessel was held to the minimum amount required for the necessary instrumentation. While data were recorded, the surgical retractors were removed from the wound in order to restore the vessel to conditions as nearly physiological as possible. A 1% solution of lidocaine was applied to the vessel wall prior to the recording of data in three patients.

Changes in the diameter of the common carotid artery were measured with an electrical strain gauge caliper. The legs of this instrument were tightly sutured in three places to the adventitia of the vessel wall as close to a diameter as possible (fig. 1). Change in length of the carotid artery was measured with the same instrument by resuturing it to the long axis of the vessel. Displacement of one leg of the caliper with respect to the other will result in a proportional change in the electrical resistance of the strain gauge. The amplitude response of this instrument...
TABLE 1
Summary of Clinical and Experimental Data

<table>
<thead>
<tr>
<th>Patient no.</th>
<th>Diagnosis</th>
<th>Age (years)</th>
<th>Blood pressure</th>
<th>Diastolic radius R (cm)</th>
<th>Area change (%)</th>
<th>$\Delta L/L_0^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Aneurysm</td>
<td>53</td>
<td>193 (cm H$_2$O)</td>
<td>132 cm H$_2$O</td>
<td>.361 + .005</td>
<td>4,404</td>
</tr>
<tr>
<td>2</td>
<td>Tumor</td>
<td>36</td>
<td>146</td>
<td>107 cm H$_2$O</td>
<td>.525 + .003</td>
<td>4,693</td>
</tr>
<tr>
<td>3</td>
<td>Tumor</td>
<td>55</td>
<td>171</td>
<td>122 cm H$_2$O</td>
<td>.425 + .005</td>
<td>4,156</td>
</tr>
<tr>
<td>4</td>
<td>Carotid stenosis</td>
<td>60</td>
<td>220</td>
<td>116 cm H$_2$O</td>
<td>.462 + .005</td>
<td>9,610</td>
</tr>
<tr>
<td>5</td>
<td>Causalgia</td>
<td>41</td>
<td>134</td>
<td>100 cm H$_2$O</td>
<td>.463 + .005</td>
<td>3,148</td>
</tr>
<tr>
<td>6</td>
<td>Aneurysm</td>
<td>47</td>
<td>250</td>
<td>127 cm H$_2$O</td>
<td>.414 + .007</td>
<td>7,275</td>
</tr>
<tr>
<td>7</td>
<td>Tumor</td>
<td>28</td>
<td>160</td>
<td>115 cm H$_2$O</td>
<td>.373 + .003</td>
<td>5,595</td>
</tr>
<tr>
<td>8</td>
<td>Aneurysm</td>
<td>45</td>
<td>184</td>
<td>126 cm H$_2$O</td>
<td>.444 + .003</td>
<td>8,492</td>
</tr>
<tr>
<td>9</td>
<td>Tumor</td>
<td>36</td>
<td>150</td>
<td>107 cm H$_2$O</td>
<td>.494 + .004</td>
<td>6,052</td>
</tr>
<tr>
<td>10</td>
<td>Tumor</td>
<td>69</td>
<td>150</td>
<td>99 cm H$_2$O</td>
<td>.447 + .003</td>
<td>8,493</td>
</tr>
<tr>
<td>11</td>
<td>Tumor</td>
<td>50</td>
<td>145</td>
<td>100 cm H$_2$O</td>
<td>.458 + .003</td>
<td>6,870</td>
</tr>
<tr>
<td>12</td>
<td>Tumor</td>
<td>50</td>
<td>136</td>
<td>98 cm H$_2$O</td>
<td>.306 + .003</td>
<td>3,978</td>
</tr>
<tr>
<td>13</td>
<td>Tumor</td>
<td>38</td>
<td>206</td>
<td>152 cm H$_2$O</td>
<td>.402 + .003</td>
<td>7,290</td>
</tr>
</tbody>
</table>

* Signs in columns 7 and 10 note the direction of change of the vessel wall, i.e., (+) increase and (−) decrease.

was flat (±5%) to 20 cycles/sec. The phase lag was negligible through 20 cycles/sec. The measurement error, due to the mechanical impedance of the caliper, has been found to be approximately 0.5%. The recording characteristics are believed to be adequate for this study. The caliper was connected to a Sanborn, 1500 series, strain gauge amplifier. Calibration of the instrument was done immediately following each use by fixing the device to a micrometer stand and separating the legs by known increments of displacement. The response of the instrument was found to be essentially linear over the range of displacements encountered in the study.

FIGURE 1
Schematic drawing of common carotid artery showing caliper sutured across the diameter of the vessel and the pressure transducer in place.

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In ten patients the lateral intravascular pressure was measured directly under the caliper using a short-bevel 18-gauge needle connected directly to a Statham P23Db strain gauge, figure 1. In order to obtain a lateral pressure the lumen of the needle was carefully oriented to face the vessel wall and thus be perpendicular to the direction of blood flow. The frequency response of this system was underdamped but was linear (±5%) through 20 cycles/sec. In three patients pressure was measured through a short polyethylene catheter introduced into the superior thyroid artery and connected to the Statham gauge. Data were recorded either by a Honeywell, model no. 1508, visicorder or by a Sanborn, model no. 850, direct-writing oscillograph.

In calculating the data, average values obtained from five consecutive pressure-diameter or pressure-length complexes were used. For convenience, all diameter measurements were converted to radius. The following data were obtained: the greatest change of pressure, in cm of water, (ΔP), the maximum change of radius, in cm, (ΔR) and the maximum change of length, in cm, (ΔL). The change of systolic area of the vessel as per cent of the diastolic area was calculated. A pressure-strain elastic modulus ($E_p$) was determined using the following formula:

$$E_p = \frac{\Delta P \cdot R_d}{\Delta R}$$  \hspace{1cm} (1)

where $R_d$ is the value of vessel radius, at the end of diastole. The length changes were expressed as $\Delta L/L_d$ where $L_d$ is the end diastolic length of the vessel segment. The pressure and radius data from ten patients (those in whom the pressure was measured directly with the needle) were subjected to Fourier analysis to 20 cycles/sec with a Honeywell 800 digital computer using standard programming techniques.

**Results**

The results from thirteen patients are summarized in table 1. In patients numbered 1, 2, and 3 (table 1) the vessel radius was found to decrease with increasing pressure (fig. 2B). In patients 1 and 2 (table 1), this finding was reversed by applying longitudinal tension to the vessel distal to the point of measurement. In patient number 3 (table 1), the increase in radius with systole (fig. 2A) was reversed repeatedly (fig. 2B) by applying tension laterally to the vessel walls with a retractor, so that the cross section of the vessel was made slightly elliptical. In the remaining patients, circumferential strain increased with increase in distending pressure. The configuration of the intravascular pressure and the vessel radius tracing are similar as noted in figures 2A, 3A, and 4A. The mean value of end diastolic vessel radius was 0.429 cm (± 0.058), and the mean $\Delta R$ was 0.004 cm (± 0.001). The mean change in cross-sectional area was $2.10 \%$ (± 0.08) of the end diastolic area. The mean value of $E_p$ was 6158 g cm$^2$ (± 1763). The magnitude of $E_p$ was not directly related either to the level of diastolic blood pressure or to the age of the patient. In the three studies in which lidocaine was applied to the vessel prior to the recording of data, the values of circumferential strain were similar to those found in other subjects.

In figure 5, mean values obtained from the Fourier analysis of the pressure tracing (A) and radius tracing (B) are charted as functions of frequency. The zero frequency term
FIGURE 3
A: Records of lateral pressure (P) and vessel radius (R). B: Lateral pressure (P) and vessel length (L). Note that vessel is elongating with systole.

FIGURE 4
A: Records of lateral pressure (P) and vessel radius (R). Note similarity of these two curves. B: Records of lateral pressure (P) and vessel length (L). Note that the vessel is shortening with systole.

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refers to the average value of pressure or radius, respectively. The other black bars represent the mean value of the various moduli in the harmonic series. The small crossed bars represent the standard error (SE) of each of the moduli. Note that moduli for both pressure and radius decrease similarly with increase in frequency, so that after 10 cycles/sec the value of both moduli merged into the noise level of the recording system.

In ten patients the relation between intravascular pressure and longitudinal strain was studied. In four patients the strain increased with increasing pressure (fig. 3B). In these patients the mean ratio $\Delta L/L_d$ was $+0.010$ ($\pm 0.002$). In six subjects the longitudinal strain decreased with systole (fig. 4B) showing a mean $\Delta L/L_d$ of $-0.013$ ($\pm 0.006$).

**Discussion**

In any physiologic study of the cardiovascular system in which a surgical dissection must be performed prior to the collection of data, the results must be interpreted with caution. In the present study exposure of the common carotid artery and, thus, alteration of the normal attachments of the vessel was necessary. However, as noted in the description of methods, this dissection was held to a minimum. Surgical instruments which might distort the normal anatomy were removed prior to the collection of data. Arterial spasm was not observed. Thus we feel that the data were obtained under conditions as nearly physiologic as possible.

The surprising finding that a segment of vessel can actually show a decrease in cir-
Cumferential strain in response to increase in distending pressure was first noted by Wehn \(^7\) in the femoral artery of rabbits. Wehn interpreted this result as evidence for a pump-like action of the vessel wall. There are two other more reasonable explanations for this observation. The vessel can have a noncircular radial configuration so that when the intravascular pressure increases, the major semi-axis of the ellipse will decrease. A recording instrument, such as our caliper, measuring this dimension, will then measure a decrease in strain. This hypothesis was clearly demonstrated by patient number 3 (table 1 and fig. 2) and was probably present in the other two patients, numbers 1 and 2, in whom a systolic decrease in circumferential strain was recorded. The alternate explanation is that the vessel segment is elongating during systole and tending to decrease the radius. This decrease of circumferential strain during systole has not been observed in either the human ascending aorta \(^5\) or the pulmonary artery \(^8\) studied by the same technique. Nor has it been noted in similar studies of the aorta or brachiocephalic artery of the dog.\(^2\) However, in areas of the body, such as the neck, or femoral triangle where the artery passes over large muscle bundles and is subjected to twisting, it would seem reasonable that an out-of-round radial configuration might exist normally.

A good degree of similarity in the shapes of the intravascular pressure and radius curves is illustrated in figures 2, 3, and 4. This similarity suggests that to a first approximation, the vessel wall can be considered to be predominantly elastic with only minor viscous or inertial properties. The \(\Delta R\) in the common carotid was very small. Thus the mean systolic change in cross-sectional area was only 2.10\% greater than the end diastolic area. This finding can be contrasted with a mean systolic cross-sectional area change of 11\% in the human ascending aorta.

The use of a simple pressure strain elastic modulus such as \(E_p\), as an index of vessel wall properties in vivo must be interpreted with caution, because the effects of an out-of-round configuration, vessel tethering, and longitudinal strain are ignored. However, the mean value of \(E_p\), 61.58 g cm\(^{-2}\), is greater than that noted in the brachiocephalic artery of the dog.\(^2\) It is also considerably greater than the mean value for \(E_p\) of 71.5 g cm\(^{-2}\) obtained in the human ascending aorta.\(^5\) The greater value of \(E_p\) noted in the carotid artery may be due to either the geometric effect of a smaller vessel radius or to an actual increase in the stiffness of the vessel wall. Obviously, the vessel wall thickness could not be measured accurately in these patients. However, the ratio of \(R/h\) where \(h\) is the wall thickness, is known to be relatively constant for large blood vessels.\(^4\) If Poisson’s ratio is 0.5 \(^9\) and \(R/h\) is constant, then \(E_p\) can be shown to be similar to Young’s modulus.\(^4\) Thus an increase in \(E_p\) would signify an actual increase in vessel wall stiffness.

The longitudinal strain was measured in ten subjects. In six patients, the strain decreased (fig. 4B), and in the other four, it increased (fig. 3B) with systole. The magnitude of this change was relatively small, being about 1.0\% of the end diastolic length of the vessel segment. A similar finding, that of shortening of the dog abdominal aorta during systole, was noted by Patel et al.\(^10\) Patel et al. attributed it to firm tethering of the distal abdominal aorta and systolic elongation of the descending thoracic aorta. If the ascending aorta elongated during systole, then a similar mechanism might explain a decrease of longitudinal strain noted in these six patients. Thus, it seems that the longitudinal motions of a segment of the common carotid artery at any given time are the result of an extremely complex relationship between the effects of local stress, due to the intravascular pressure and flow, and more remote stresses which are modified by vessel tethering.

**Summary**

The relationships between lateral intravascular pressure, vessel radius, and vessel length were evaluated in the common carotid artery in vivo in thirteen patients during treatment by surgery. Strain was measured in the wall.
of the carotid artery by means of an electrical caliper sutured to the vessel wall. Lateral intravascular pressure was measured directly with either an 18-gauge needle or a short polyethylene catheter connected to a Statham, P23Db, strain gauge. The results indicate that circumferential and longitudinal strains in the common carotid artery were both small. The mean systolic change in cross-sectional area was 2.10% (± SD 1.08) of the end diastolic area. In three patients a negative circumferential strain was produced by making the cross section of the vessel elliptical. During systole, longitudinal strain increased in four patients and decreased in six patients. The average change in vessel segment length during systole was approximately 1.0% of the end diastolic length.

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