A nondestructive technique to measure wall displacement in the thoracic aorta

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The purpose of the present paper is to present a rapid nondestructive technique to follow aortic wall motion and thereby measure the fluctuations in thoracic aortic diameter which occur with pulsatile pressure changes. Many methods for measuring diameter contours have been used in the past, but all have some disadvantages.

One group of methods involves the surgical implantation of dimension gauges (2, 9, 8). Invasive techniques such as these lead to low estimates of arterial distension, compared to noninvasive techniques (1, 4, 6). Surgically induced scar tissue in chronic experiments and vessel spasm in acute ones conceivably could alter wall motion. Even slight disruption of the tethering effect of peri- vascular tissue may interfere with pressure-diameter-length relationships.

On the other hand, those methods which use noninvasive techniques often suffer from loss of resolution. Angiographic techniques (4), for example, are ideal in that they do not disturb the normal physiology of the region being studied, but they do not have the necessary resolving power to follow very small displacements.

The new technique presented here not only is nondestructive but also has resolving power to track displacements in the order of microns. Repeated measurements can be made over extended periods of time.

INSTRUMENTATION

Before proceeding with a detailed description of the instruments and their specifications, an overall view of the general technique seems advisable. In this study, a transesophageal approach to the aorta was used, i.e., the crystal generating and receiving sound waves was placed on a tube which was passed down the esophagus to the level of the aortic arch. The walls of the aorta were then tracked by shooting ultrasound through the esophagus. To help establish the validity of the technique, pressure tracings were recorded from the same aortic site at which the diameter measurements were made.

The ultrasonic system consists of a rectangular, 5 x 7 mm, 5 mc, lead titanate zirconate crystal attached to the end of a plastic esophageal probe (Fig. 1). The end of the probe, a white plastic cylinder containing the crystal, is shown in the encircled insert (upper left) within Fig. 1. About halfway down the cylinder, the crystal is attached to a platform which allows the tilt of the crystal to be adjusted. The pivot point of this platform can be seen as a black dot. To the left of this dot is the crystal with wires attached to each of its surfaces. These wires pass through the plastic tubing of the probe in the shielded cable. The critical feature is the fact that the tilt of the crystal can be adjusted from the outside when the crystal is in position down the esophagus.

The power source consisted of a Nortec model NDT 100 plug-in which supplied a 2 μsec burst of electrical energy to the crystal at a repetition rate of 2 kHz, the peak voltage being 25 v. The signal produced by the echo was fed to the Nortec amplifier using a 5- to 20-MHz bandwidth and moderate damping. The output of the amplifier was displayed on a Tektronix 551 oscilloscope shown schematically in Fig. 1.

Motion pictures (80 frames/sec) of the face of the oscilloscope were taken, and these were read frame by frame. Figure 2 shows two such frames. Comparing the bottom frame to the top frame, one finds a minute shift, to the left, of the spikes in the pulse-echo trace. This indicates slight motion of the reflecting site toward the crystal.

The characteristics of the system were checked statically and dynamically. The static calibration was done with a depth micrometer, and the system was found to be linear to the 0.04-mm level. A scale factor based on the speed of ultrasound in tissue was used to convert transit time to distance. This factor is essentially the same (±5%) in all the tissue involved in these experiments (blood, muscle, fat, etc., but not bone) and the value of 1,570 m/sec was used. The dynamic response of the system was tested by moving a reflecting surface so that the distance between it and the crystal varied sinusoidally with time. The output of the system was then compared with the known sine-wave displacement. It was found that the system had a flat frequency response with no detectable phase shift within the spectrum of anticipated experimental frequencies (2-20 Hz). Furthermore, filmed data were read and analyzed by a digital computer. From the computer analysis it was found that there was no spurious harmonic, the amplitude of which was greater than 0.04 mm. The actual apparatus used in the dynamic calibration is shown and described in Fig. 3.
edge of these characteristics was necessary. It became apparent early in these experiments that the amplitude and shape of the echo-wave packet depended strongly on the angles between the crystal and the reflecting surface. To study this relationship more completely, the water bath shown and described in Fig. 1 was developed. The angles and distances between the crystal and the reflecting surface could be measured precisely. Reflections from both planar and cylindrical surfaces were studied. Figure 4, A and B, shows how the shape of the echo changes with the indicated angle between the crystal and a planar surface. Within limits, the larger the crystal, the more sensitive the shape of the trace is to this angle. When the crystal was lined up so as to study reflections from the simulated aorta the following effects were noted. When the ultrasonic beam was directed along the diameter, the echo trace looked much like that in Fig. 4A. If the sonic beam was slightly off the diameter, however, the packet changed shape and looked more like that in Fig. 4B. The echo trace did not change...
Although the pulse-echo technique could be used to measure wall motion at a number of sites along the aorta, the probe was positioned at the level of the arch for a number of reasons. First, it is shown in Fig. 5. With the esophageal probe in place and the echo trace from the near wall created only one maximum and one minimum with each beat, indicating that the echo trace moved less than half a wavelength and that the maximum excursion of the near wall was less than 0.08 mm. For most experiments the near wall moved close to 1.4 mm so that the motion of the near wall was less than 0.08%. The frequency response of the catheter-manometer system was tested, as reported in a previous paper (7), and the natural frequency was well above 120 Hz, with damping factor $h = 0.6$. The overall characteristics of both the pulse-echo and pressure systems were also tested using the apparatus just described (Fig. 6). The same drive shaft which produces the sinusoidal displacement of the reflecting surface in the water bath, B, also produces sinusoidal changes in the pressure records at point D. When the output from the pressure transducer at point D and the pulse-echo system were displayed on the oscilloscope and analyzed, no deviation from the expected 90° phase shift was detectable. Fourth, dissection verified that the arch of the aorta passes just to the left of the esophagus and that when the animal was moved to the right lateral decubitus position, the arch falls to rest on the esophagus and its indwelling probe. It should be apparent that positioning of the probe relied on echoes received from the far wall of the aorta, which were easy to pick up. Signals from the near wall were identified next and presented unique problems at the chosen site. These signals lay buried in the signal generated by the ringing crystal. Figure 1, discussed previously, can be used to clarify this. Shown diagrammatically in the center of the face of the oscilloscope is a series of spikes representing the echo trace from a single reflecting surface relatively far from the crystal, such as the far wall of the aorta. If the reflecting site were closer to the crystal as is the case with the near wall the echo trace would fall in the series of spikes at the extreme left, which represent ringing of the crystal. In this case, when the echo trace lines up with the stationary waves so that the peaks of the former occur simultaneously with the peaks of the stationary wave, a series of relatively large spikes will result from the addition of sine waves. On the other hand, when the minima of the echo trace line up with the maxima of the stationary wave, partial cancellation leads to relatively small spikes. As the echo trace moves through the stationary wave, a cyclic variation in the height of the resultant spikes occurs. In these experiments, motion of the near wall created only one maximum and one minimum with each beat, indicating that the echo trace moved less than half a wavelength and that the maximum excursion of the near wall was less than 0.08 mm. For most experiments the far wall moved close to 1.4 mm so that the motion of the near wall was less than 0.08% of the far wall. Frequently the validity of this estimate could be checked directly because the stationary wave had a few very low amplitude spikes on which the echo trace could be seen moving laterally without detectable variation in the amplitude of its spikes. These movements were too small to analyze, but on a miniature scale roughly paralleled movements of the far wall.

With the esophageal probe in place and the echo trace from both walls located, the carotid artery was exposed and the stainless steel catheter was positioned so that its tip was lying opposite the crystal in the distal part of the aortic arch. As already stated, the probe and catheter had previously been marked to indicate equal lengths so that they could be inserted to equal depths. The position of both devices was confirmed by fluoroscopy in some cases. The following procedure, done after the data were collected, also con-
The near wall. Figure 6 shows simultaneously recorded pressure motion of the far wall was used, and so the near wall appeared as to follow the motion of the far wall, and a third to follow the motion practically stationary and was considered as fixed. As noted above, settings were used, one to measure the mean diameter, another to loscroscope would have to be close to 2 m wide in order to see the re-motion would be completely inappropriate to follow the distance between the two walls. For example, if 1 mm on the oscilloscope screen and pressure and diameter were read frame by frame, the were analyzed as wishments was checked by means of the Moens-Korteweg equation. Other investigators (2) have consistently found a close agreement between pressure and diameter contours, and Fig. 6 shows that the wave velocity in the aorta

<table>
<thead>
<tr>
<th>Exp No</th>
<th>Pulse Pressure (AP)</th>
<th>Percent Strain (AD/DF X 100)</th>
<th>Wave Velocity (C)</th>
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<tbody>
<tr>
<td>1 (Fig. 6)</td>
<td>50.5</td>
<td>5.8</td>
<td>7</td>
</tr>
<tr>
<td>2</td>
<td>41.3</td>
<td>8.0</td>
<td>6</td>
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<td>8.5</td>
<td>5</td>
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<td>4</td>
<td>31.0</td>
<td>8.5</td>
<td>5</td>
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<tr>
<td>5</td>
<td>41.5</td>
<td>9.8</td>
<td>5</td>
</tr>
<tr>
<td>6</td>
<td>39.5</td>
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</tr>
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<td>Avg</td>
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<td>8.5</td>
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The data, which were recorded in movics of the oscilloscope, were analyzed as follows. The film was projected onto a small screen and pressure and diameter were read frame by frame, the diameter being taken as the indicated distance between near and far wall. As will be discussed below, the excursions of the far wall are close to 10% of the mean diameter, and those of the near wall are about 0.5%. A scale factor (dial setting on the oscilloscope time base) which would be appropriate to follow the near wall motion would be completely inappropriate to follow the distance between the two walls. For example, if 1 mm on the oscilloscope represented 10 μ so as to follow near wall motion, then the oscilloscope would have to be close to 2 m wide in order to see the reflections from the far wall simultaneously. Therefore three dial settings were used, one to measure the mean diameter, another to follow the motion of the far wall, and a third to follow the motion of the near wall. Figure 6 shows simultaneously recorded pressure and diameter contours. A scale factor appropriate to follow the motion of the far wall was used, and so the near wall appeared as practically stationary and was considered as fixed. As noted above, a maximum error of 6% in the estimation of peak excursion results from this assumption.

Validity of technique. The validity of the data was checked in two ways. First, the diameter contours were compared to the recorded pressure contours. Second, the magnitude of the diameter excursions was checked by means of the Moens-Korteweg equation. Other investigators (2) have consistently found a close agreement between pressure and diameter contours, and Fig. 6 shows that the present technique also produces the expected similarity of contours. The close similarity of contours is most impressive when one realizes the magnitude of the discrepancies involved. Figure 6 shows typical contours even though the dog was hypertensive. It was chosen because, during diastole, the pressure happens to fall almost linearly so that the oscillations of the diameter values around those of the pressure are obvious. Note that the amplitude of these oscillations is in the order of 30 μ. The close agreement of pressure and diameter contours thus supports the validity of the technique.

Table 1 shows another way in which the data were checked. The pulse pressure (ΔP) and percent strain (ΔD/DF X 100, where D represents aortic diameter) are tabulated along with calculated wave propagation velocities (C). The Moens-Korteweg equation, \( C = \frac{0.67 \cdot g \cdot \Delta P / \Delta T}{p \cdot \rho} \) (where g is the gravitational constant, \( \rho \) the density of blood, and \( \rho \) the strain, i.e. \( \Delta D/D \)), was used in these calculations.

The average aortic diameter was 16 mm, with minimal variation from one animal to the next (+/-10%). The calculated wave velocity had an average value of 5 which agrees well with previously reported wave velocities. This agreement between calculated and expected values suggests that the diameter data on which the calculations were based must be reasonable.

Critique of method. One of the main criticisms of ultrasonic pulse-echo techniques has been that, when relying on one-dimensional time-amplitude systems, it is often difficult to identify structures and verify artifacts (3). However, in a series of six dogs, the distal wall of the aorta was so easy to locate and identify that it could be used as a landmark to locate other structures in the thorax.

The auraline impedance matching of two media determines the strength of the reflection from their interface. The impedance mismatch at an air-tissue interface is very great, and therefore the reflection is virtually total. For example, ultrasound does not readily lend itself to transthoracic measurement. With a transesophageal approach, the outside of the distal aortic wall is air backed. The interface acts as an ideal reflector and gives a signal-to-noise ratio of 25 db. Such a strong reflection often causes multiple echoes or reverberations. These artifacts are easily recognized and disregarded because they appear at multiples of the original echo's distance and indicate greater pulsatile excursions. Other types of artifacts are unlikely because of the proximity of the aorta to the crystal.

The ultrasonic signal was originally processed using a gated system similar to that of Hakanen et al. (6), whereby the transit time, representing distance, was converted to a voltage readout. However, in our study, obtaining high resolution and monitoring the signal stability required the use of a high-speed movie camera. As previously described, one could read these films to within ±0.04 mm. This is not surprising since Giglio et al. (5) were able to measure intraocular distance to within ±0.016 mm using higher frequencies.

In summary, a rapid, nondestructive technique to follow the motion of the wall of the thoracic aorta has been presented. The technique always works, produces very precise data, and can be repeated in the same animal as desired.

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The animals involved in this study were maintained in accordance with the "Guide for Laboratory Animal Facilities and Care" as published by the National Academy of Sciences—National Research Council.

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REFERENCES


