Operational Sensitivity and Acute Resetting of Aortic Baroreceptors in Dogs

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SUMMARY  Stimulus-response curves of aortic baroreceptors constructed by alternately increasing and decreasing pressure from a normal baseline or set-point differ from curves constructed by varying pressure in one direction only from an abnormally high or low pressure. In anesthetized dogs we recorded impulses from aortic baroreceptors with myelinated fibers, using a pressurized reservoir to control mean aortic blood pressure (MABP). After setting MABP to a baseline of 100 mm Hg (normal MABP in unanesthetized dogs), we constructed baroreceptor response curves by alternately decreasing MABP from 100 to 30 mm Hg, and increasing it from 100 to 180 mm Hg, in each case returning MABP to the baseline to obtain hysteresis loops. All baroreceptors were active at 100 mm Hg, their discharge averaging 15-16 impulses/sec. At all pressures above threshold, baroreceptors fired more when pressure was increasing than when pressure was decreasing. This hysteresis caused the steepest part of the response curve constructed in this manner to span the baseline value, demonstrating that, contrary to previous views, aortic baroreceptors signal decreases in pressure below the normal level, as well as increases above it. We also constructed response curves after holding MABP at a "hypertensive" baseline of 125 mm Hg for 20 minutes. "Hypertensive" curves demonstrated reversible resetting, shifting significantly to the right of "normotensive" curves so that baroreceptor threshold increased on average by 7 mm Hg (P< 0.01). Both hysteresis and short-term resetting probably result from the viscoelastic behavior of wall elements with which baroreceptors are coupled.


THE ROLE of aortic baroreceptors in regulating blood pressure is controversial. From the results of an electroneurographic study in dogs, Pelletier et al. (1972) concluded that at normal arterial pressure the aortic nerve displays little baroreceptor activity and that, rather than acting as a true buffer system, aortic baroreceptors have a predominantly antihypertensive role. However, two recent studies in conscious dogs indicate that when the carotid sinus nerves are cut the aortic nerves alone can buffer decreases, as well as increases, in arterial pressure (McRitchie et al., 1976; Ito and Scher, 1978). This apparent conflict of evidence about a fundamental aspect of the functions of aortic baroreceptors in dogs suggests that a reexamination of their afferent properties is timely.

In studies of the stimulus-response characteristics of arterial baroreceptors, the common practice is either to increase pressure until firing frequency is maximal and then to examine baroreceptor response as pressure is reduced (Fig. 1A), or to reduce pressure below baroreceptor threshold and then to examine the response as pressure is increased (Fig. 1B) (Angell-James, 1971; Pelletier et al., 1972; Angell-James, 1973; Brown et al., 1976; Sleight et al., 1977; Thoren and Jones, 1977; Kaufman et al., 1978). However, as Angell-James (1971) has shown in rabbits, and as Pelletier et al. (1972) and Brown et al. (1976) subsequently have confirmed in dogs and rats, respectively, the upward and downward pressure-response curves of aortic baroreceptors are different, and at any given pressure baroreceptor discharge is greater when pressure is increasing than when it is decreasing. In vivo, the common physiological disturbances of arterial blood pressure, such as those associated with changes in posture, consist of increases above and decreases below a normal baseline pressure (Fig. 1C), so that directional sensitivity or hysteresis is probably an integral part of normal, moment-to-moment baroreceptor operation. A conventional stimulus-response curve that, originating at one or other extreme of the baroreceptor response, takes no account of this directional sensitivity clearly cannot furnish an accurate representation of baroreceptor operation around the set-point (Fig. 1).

With these considerations in mind, we reexamined in dogs the firing rate of aortic baroreceptors with myelinated fibers to determine their activity at normal aortic blood pressure. To construct pressure-response curves, we varied mean aortic pressure at a constant rate, alternately increasing it above and decreasing it below the control baseline, and combined the two parts of the pressure-response curve so obtained into a single curve that represented the baroreceptor response to pertur-
ARTERIAL BLOOD PRESSURE

FIGURE 1 Hypothetical pressure-response curves of aortic baroreceptors. Curves A and B obtained by changing pressure in one direction: A, descending curve obtained by decreasing pressure from a maximum; B, ascending curve obtained by increasing pressure from a subthreshold minimum; C, curve obtained by changing pressure above and below an intermediate baseline or set-point, which in the present experiments corresponded to a mean arterial blood pressure of 100 mm Hg.

Aortic baroreceptors with myelinated fibers, constructing additional pressure-response curves in a similar manner from a higher or a lower baseline.

Methods

General

Dogs (11–27 kg) were given promazine hydrochloride (Sparine, Wyeth Laboratories (50 mg, im); 1 hour later they were anesthetized with 0.25 ml/kg, iv, of a 1:1 mixture of solutions of Dial Compound (allobarbital 100 mg/ml, urethane 400 mg/ml, Ciba) and sodium pentobarbital (50 mg/ml). Tidal Pco2 was monitored continuously by a Beckman LB-1 gas analyzer. Blood pressure in the aortic arch was recorded with a Statham P23Gb strain gauge, through a catheter inserted via the right carotid artery. An electrocardiogram was recorded; heart rate was recorded by a tachograph triggered by the ECG. With the aid of conventional techniques, action potentials were recorded from aortic baroreceptor fibers of the left aortic nerve (see below) and were counted by a ratemeter (Rate/Interval Analyzer, Frederick Haer & Co). After amplification, action potentials, ratemeter output and other variables were recorded by an ultraviolet light recorder (SE Laboratories) and all but the action potentials were recorded by a Grass polygraph. Aortic pressure was displayed on two channels simultaneously, pulsatile pressure on one, and an electronically damped record of mean pressure on the other.

Control of Arterial Blood Pressure

In preliminary experiments on dogs with open chest, we increased and decreased arterial blood pressure by tightening snares placed round the descending aorta and inferior vena cava, but we made no attempt to regulate the control or baseline arterial pressure. In other experiments on dogs with closed chests, we controlled arterial pressure more precisely, and kept it at a constant baseline between experiments, using a regulating device similar in most respects to that used by Pelletier et al. (1972). A wide-bore catheter, placed in the abdominal aorta through a femoral artery, was connected to a pressurized reservoir (5 liters) containing equal volumes of 6% Dextran 70 in 0.9% NaCl solution (Cutter Laboratories) and blood taken from another dog. Heparin (1000 U) was added to the blood in the reservoir; we also gave heparin (100 U/kg, iv) to the dog. A reservoir of air (20 liters) was connected to the top of the blood reservoir to minimize pressure oscillations in the system and to give smoother control of arterial blood pressure. Air pressure in this system determined the level of mean aortic blood pressure and was itself regulated by means of a variable inflow of compressed air and a variable leak. The reservoir of blood was placed in a water bath maintained at 37°C.

Recording of Baroreceptor Impulses

Afferent filaments were dissected from the left aortic nerve in the upper cervical region, and action potentials were recorded from baroreceptor fibers with conduction velocities greater than 10 m/sec. In the dog, the aortic nerve lies within the vagal sheath, but usually it can be distinguished from the remainder of the common vagosympathetic trunk when the sheath has been removed. The identity of the aortic nerve was confirmed by the characteristic baroreceptor discharge obtained when the nerve was separated from the vagal trunk and placed intact on the recording electrodes. Individual baroreceptor fibers were identified by the characteristic timing and pattern of discharge, and in open-
chested dogs we verified the position of receptors by probing the aortic arch. We attempted to avoid bias toward low-threshold receptors as follows. When searching for baroreceptor fibers in the preliminary experiments, we tested each strand of aortic nerve for the presence of inactive high-threshold fibers by snaring the aorta to increase blood pressure. When searching for baroreceptors in the later experiments, we used the pressure regulator to keep mean aortic pressure between 120 and 130 mm Hg. We measured conduction velocities by stimulating the vagosympathetic trunk low in the neck at two points 2 cm apart through two pairs of electrodes fixed in a shielded assembly, and derived conduction velocity from the conduction time between the stimulating electrodes.

Heparin, administered iv and added to the blood in the pressure regulator, made conditions for single fiber dissection and recording difficult because blood oozed from the tissues and contaminated the mineral oil covering the nerve and electrodes. However, by lining the recording pool with thin plastic sheeting, we were able to keep the mineral oil free from blood for several hours of recording.

**Baroreceptor Stimulus-Response Curves**

We constructed stimulus-response curves as follows. We used the blood pressure regulator to set mean aortic pressure to the initial baseline (100 mm Hg in most cases) and to maintain it at this level for 20 minutes before starting our observations. From this baseline we then, in turn, increased and decreased mean aortic pressure by slow ramps of approximately 1 mm Hg/sec to a minimum of 30-40 mm Hg and to a maximum of 180 mm Hg, recording baroreceptor activity continuously. With both downward and upward curves we obtained hysteresis loops by slowly returning mean aortic pressure to the baseline at the rate of 1 mm Hg/sec. Downward and upward curves were obtained in random order. Atropine sulfate (0.5 mg/kg, iv) and propanolol hydrochloride (0.5 mg/kg, iv) were given as required to prevent changes in heart rate when arterial blood pressure was changed.

We determined thresholds for individual baroreceptors by estimating the lowest mean aortic pressure at which single pulse-related action potentials still occurred as pressure was decreased, and the lowest mean aortic pressure at which single pulse-related action potentials began to occur as pressure was increased. In each case thresholds were measured to the nearest mm Hg.

For some aortic baroreceptors we constructed two pressure-response curves, one from a baseline of 100 mm Hg, as described above, the other from a baseline of either 75 or 125 mm Hg, which was always maintained for 20 minutes before the response curve was obtained. Curves from the higher and lower baselines of each pair were made in random order.

When constructing pressure-response curves, we averaged baroreceptor firing (impulses/sec) over 5-7 cardiac cycles during expiration at intervals of 10 mm Hg above and below the baseline pressure. We used Student’s paired t-test to compare each measurement of impulse frequency made as pressure was increased with that made at the corresponding pressure as pressure was decreased. We compared the Pearson product-moment correlation coefficient (r) (Snedecor and Cochran, 1967) between the increment in firing frequency and the increment in pulse pressure for each 10 mm Hg increase or decrease in mean pressure along the pressure-response curve.

Pressure-response curves from different baselines were compared by analysis of variance for 2-factor repeated measurements (Snedecor and Cochran, 1967). Values are expressed as the mean ± SEM.

**Results**

**Preliminary Experiments**

We recorded impulses from 29 aortic baroreceptor fibers with conduction velocities of 11.2-48.1 m/sec (mean ± se, 27.9 ± 2.1), dissected at random in 19 dogs with open chests. In the control period, mean aortic blood pressure averaged 100.8 ± 3.2 mm Hg and firing frequency averaged 15.3 ± 1.7 impulses/sec. We determined the pressure thresholds of 22 of these fibers by first tightening and then releasing a snare round the inferior vena cava. The rate of change of pressure varied in individual experiments from 2 to 6 mm Hg/sec. The threshold at which fibers fired a single impulse with each cardiac cycle as pressure was decreasing (86.3 ± 3.1 mm Hg) differed significantly from the threshold at which fibers fired a single impulse with each cycle when pressure was increasing (72.6 ± 2.7 mm Hg; P < 0.001).

We also determined the thresholds of 15 aortic baroreceptors in a single dog (fiber conduction velocities, 14.7-44.2 m/sec). The average threshold to decreasing pressure was 88.5 ± 5.1 mm Hg, and that to increasing pressure was 76.3 ± 4.5 mm Hg.

**Functional Pressure-Response Curves**

In experiments on eight dogs, we constructed pressure-response curves, using a pressurized reservoir to vary pressure at a constant rate above and below an arbitrary baseline or set-point. We avoided changes in heart rate, and the associated changes in pulse pressure, by administering atropine and propanolol.

We recorded the activity of 35 aortic baroreceptors with myelinated fibers (conduction velocities, 13.9-45.6 m/sec; mean ± se, 29.0 ± 1.9 m/sec). All 35 baroreceptors were active when first identified at a mean aortic blood pressure that ranged from 117 to 138 mm Hg in different dogs, and all were still active after mean pressure had been adjusted...
to a baseline of 100 mm Hg and held at this level for 20 minutes, when discharge frequencies ranged from 4.5 to 33.3 impulses/sec (15.8 ± 1.0 impulses/sec). We then gradually decreased (Fig. 2) and increased (Fig. 3) mean aortic pressure from the baseline of 100 mm Hg to a minimum of 30-40 mm Hg or to a maximum of 180 mm Hg. Baroreceptor firing at baseline pressure was remarkably constant and, with only a few exceptions, returned between the two parts of the experiment to within ± 3 impulses/sec of its original value (Fig. 4).

Although many previously silent aortic baroreceptors with C-fibers (Kaufman et al., 1978) became active as pressure was increased gradually from 100 to 180 mm Hg, no additional baroreceptors with fiber conduction velocities of more than 10 m/sec were recruited. This was further evidence that, in our initial selection of fibers for investigation, we had not overlooked myelinated fibers with high-threshold endings that were inactive at the existing pressure.

Stimulus-response curves obtained in four experiments (Fig. 4) illustrate the range of sensitivities and overall responses of the baroreceptors in our sample. From such individual results, we plotted the average functional stimulus-response curve for the whole group of 35 baroreceptors (Fig. 5). The downward and upward parts together formed a curve of sigmoid shape whose steepest part between 90 and 120 mm Hg had an average slope of 1.2 impulses/sec per mm Hg.

Pulse pressure normally changes when mean blood pressure decreases or increases. By administering atropine and propanolol, we avoided the changes in pulse pressure associated with changes in heart rate. Nevertheless, there was a small but significant decrease in pulse pressure averaging 3 mm Hg when mean aortic pressure was reduced from 100 to 50 mm Hg (Fig. 2), and an increase of 20 mm Hg when mean pressure was increased from 100 to 180 mm Hg (Fig. 3). There was, however, no correlation between the successive increments in

**FIGURE 2** Effect of a gradual decrease in mean aortic blood pressure (1 mm Hg/sec) on the impulse activity of an aortic baroreceptor. Above, continuous record of mean aortic blood pressure (MABP), aortic blood pressure (ABP) and heart rate (HR). Below, in each of the seven panels are shown (from above downwards) an electrocardiogram, baroreceptor impulses, and aortic blood pressure. The panels were recorded at intervals as mean blood pressure decreased.

**FIGURE 3** Effect of a gradual increase in mean aortic blood pressure (1 mm Hg/sec) on the impulse activity of an aortic baroreceptor (same baroreceptor as that in Figure 2). The continuous record (above) and the panels (below) are as in Figure 2.
FIGURE 4 Functional stimulus-response curves of four aortic baroreceptors, illustrating the range of baroreceptor responses to changes in mean aortic blood pressure (MABP). The filled circles and continuous lines indicate baroreceptor responses at each 10 mm Hg interval when pressure was increased and decreased from the baseline of 100 mm Hg (vertical broken line). Crosses indicate baroreceptor responses as pressure was returned to baseline.

impulse frequency and the corresponding increments in pulse pressure for each 10 mm Hg interval when mean pressure was either decreased or increased (correlation coefficient r not significantly different from zero).

When mean aortic pressure was reduced from 100 to 90 mm Hg, baroreceptor discharge halved, decreasing from 14.8 ± 1.3 to 6.6 ± 0.8 impulses/sec. This was the steepest part of the downward pressure-response curve and was accomplished without a change in pulse pressure. Baroreceptor thresholds (i.e., the lowest mean pressure at which a single impulse occurred with each pressure pulse) ranged from 95 to 30 mm Hg. Three baroreceptors became silent as pressure was reduced from 100 to 90 mm Hg, and 12 were silent at 80 mm Hg. The average threshold was 72.6 ± 3.2 mm Hg. Three baroreceptors displayed a pattern of response similar to that described by Green (1967); i.e., they did not remain silent when pressure was reduced below the pulsatile firing threshold but began to fire irregularly at a frequency of 3–7 impulses/sec.

When mean pressure was brought back gradually to the baseline of 100 mm Hg, baroreceptor threshold on the ascending limb was less by 7.4 ± 0.8 mm Hg than that on the descending limb (P < 0.01). Moreover, at all pressures between threshold and baseline, impulse frequency was greater on the ascending than on the descending limb (Figs. 4 and 5), this directional asymmetry of the downward loop being highly significant for mean aortic pressures between 60 and 100 mm Hg (P < 0.001).

When mean pressure was increased from 100 to 110 mm Hg, baroreceptor activity doubled, increasing from 16.7 ± 1.4 to 32.8 ± 2.5 impulses/sec. This was the steepest part of the upward pressure-response curve. Although pulse pressure increased between 100 and 110 mm Hg, the increase was so small (1.2 mm Hg on average) that it was unlikely to have contributed appreciably to an increase in firing of this magnitude. Baroreceptor responses varied widely above 100 mm Hg; the average slope of the individual response curves between 100 and 180 mm Hg ranged from 0.3 to 1.3 impulses/sec per mm Hg, and discharge rates ranged from 31.2 to 138.2 impulses/sec at the maximal pressure of 180 mm Hg. Moreover, although the response curves of 25 of 35 baroreceptors were steepest between 100 and 110 mm Hg (Fig. 4, A, B, and D), the shapes of individual curves varied. Twenty of the 35 curves had a clear upper point of inflexion similar to that described in rabbits (Angell-James, 1971, 1973) and rats (Brown et al., 1976). The inflexion point of three curves occurred at mean pressures between 120 and 140 mm Hg, of eight between 140 and 160 mm Hg, and of nine between 160 and 180 mm Hg.

FIGURE 5 Functional stimulus-response curve of 35 aortic baroreceptors. Mean impulse frequency plotted at intervals of 10 mm Hg. The unfilled circle indicates baroreceptor impulse activity at the baseline mean aortic blood pressure (MABP) of 100 mm Hg. The filled circles and continuous lines indicate the baroreceptor response to an increase in pressure above the baseline, and the filled circles and broken lines indicate the response to a decrease in pressure below the baseline. The crosses indicate the changes in activity as pressure was returned from its highest and lowest values to its original baseline of 100 mm Hg. Results are mean ± SE.
The remaining 15 curves had no obvious inflexion in the pressure range of 100–180 mm Hg. Baroreceptor responses also varied widely in individual dogs: for example, in observations on five baroreceptors in one dog, the average slopes of the response curves between 100 and 180 mm Hg ranged from 0.4 to 1.1 impulses/sec per mm Hg, and the discharge rates at 180 mm Hg ranged from 42.8 to 115.9 impulses/sec. When mean pressure was returned to the baseline of 100 mm Hg, firing on the descending limb was significantly less \((P < 0.001)\) than that at the corresponding pressures on the ascending limb (Figs. 4 and 5).

**Intermittent Activity**

The intermittency of baroreceptor discharge, in which each burst of impulses in systole is succeeded by a period of silence in diastole, has been interpreted as indicating that the baroreceptors are operating near their threshold and that pressure actually falls below threshold in diastole (Arndt et al., 1975). Our results, like those of Brown et al. (1978), do not support this view. In our experiments, a clear separation of systolic bursts by diastolic pauses occurred at diastolic pressures as much as 20–40 mm Hg above systolic threshold. For instance, the baroreceptor whose response is depicted in Figure 2 had a systolic threshold of 66 mm Hg (mean pressure at threshold was 50 mm Hg), but diastolic pauses still were present when diastolic pressure was 92 mm Hg (mean pressure, 100 mm Hg). Moreover, the virtually continuous discharge observed when mean pressure exceeded 140–150 mm Hg often became intermittent when the direction of the pressure change was reversed, and mean pressure was decreased from 180 to 170 mm Hg.

**Baroreceptor "Resetting"**

In experiments on 11 baroreceptors, we obtained two stimulus-response curves, one from a "normotensive" baseline of 100 mm Hg, as described above, and one from a "hypertensive" baseline of 125 mm Hg (Fig. 6). The two curves were obtained in random order, and baseline pressure was maintained for 20 minutes at the start of each experiment. Both the upward and downward parts of the hypertensive curve were shifted significantly \((P < 0.01)\) to the right of the normotensive curve, threshold increasing on average by 7 mm Hg \((P < 0.01)\). However, the two curves were similar in that the steepest part of each spanned 10 mm Hg on either side of the baseline; the slopes were not significantly different. Both hysteresis curves followed the same general path when aortic pressure was returned to the respective baselines from the maximal and minimal values. At all pressures between 60 and 170 mm Hg, impulse frequency in both curves was significantly higher when pressure was increasing than when it was decreasing \((P < 0.001)\).

We compared pulse pressures on the upward and downward parts of the hypertensive curve with the corresponding pulse pressures on the normotensive curve. They were not significantly different. Indeed, at mean pressures of 150–180 mm Hg, pulse pressures on the hypertensive curve were 2.0–3.7 mm Hg higher than those on the normotensive curve—a difference that, although not statistically significant, might be expected to oppose the process of baroreceptor resetting.

In experiments on three baroreceptors, we also obtained stimulus-response curves after mean pressure had been reduced to a "hypotensive" baseline of 75 mm Hg. The hypotensive curves of two of the baroreceptors were shifted to the left of the normotensive curves so that the hypotensive thresholds were lower (Fig. 7). For example, in the three stimulus-response curves of one of these baroreceptors, obtained from baselines of 75, 100, and 125 mm Hg, the respective thresholds were 64, 79, and 85 mm Hg. The curve of the third baroreceptor did not shift when baseline pressure was reduced to 75 mm Hg.

**Discussion**

Our results provide strong support for the notion that, in dogs, the great majority of aortic baroreceptors with myelinated fibers are active at normal resting arterial pressure and thus can contribute to the progressive reduction of total baroreceptor input that occurs as pressure decreases. As a corollary, when pressure increases, most of the increased

**Figure 6** Resetting of functional stimulus-response relationship of 11 aortic baroreceptors. The normotensive curve (filled circles) was obtained by increasing (continuous line) and decreasing (broken line) mean aortic blood pressure (MABP) from a baseline of 100 mm Hg, and the hypertensive curve (unfilled circles) by increasing (continuous line) and decreasing (broken line) pressure from a baseline of 125 mm Hg. Results are mean ± SE.
pressure (MABP) was increased and decreased from a normotensive baseline of 100 mm Hg. Unfilled circles indicate the response when mean aortic blood pressure (MABP) was increased and decreased from a hypotensive baseline of 75 mm Hg.

FIGURE 7 Hypotensive resetting of the functional stimulus-response curve of an aortic baroreceptor. Filled circles indicate the response when mean aortic blood pressure (MABP) was increased and decreased from a normotensive baseline of 100 mm Hg. Unfilled circles indicate the response when pressure was increased and decreased from a hypotensive baseline of 75 mm Hg.

firing in this group of aortic baroreceptors results from augmented discharge in already active fibers, rather than from recruitment of previously inactive ones. Another conclusion is that directional sensitivity or hysteresis is present over the whole range of aortic baroreceptor response in dogs, so that the steep part of the functional pressure-response curve straddles a baseline pressure of 100 mm Hg, baroreceptor frequency decreasing markedly for relatively small reductions in pressure below 100 mm Hg, and increasing markedly for relatively small increases above it. These stimulus-response characteristics enable aortic baroreceptors in dogs to furnish a signal suitable for the correction of pressure disturbances below, as well as above, the normal set-point. Although our observations apply only to the afferent input, they afford some explanation of certain aspects of the aortic baroreceptor reflex that hitherto have been obscure (McRitchie et al. 1976; Ito and Scher, 1978).

Baroreceptor thresholds were somewhat higher when we changed blood pressure by snaring the inferior vena cava than when we changed it in a more controlled way with the regulator. We think that this difference stemmed from the more pronounced changes in pulse pressure that occurred in the former case. However, another explanation must be considered: namely, that the propranolol administered in the latter experiments altered aortic baroreceptor sensitivity. Angell-James and Bobik (1979) found that the aortic baroreceptor response curve was shifted to the left by propranolol, and that activity at 100 mm Hg, for example, increased by about 11%; Dorward and Korner (1978), on the other hand, reported a 7% reduction in activity at a given mean pressure and a slight increase in threshold. Even so, propranolol seemed to be without appreciable effect on baroreceptor performance in our experiments, for firing averaged 15.8 impulses/sec at a baseline mean pressure of 100 mm Hg in dogs that received the drug and 15.3 impulses/sec at an average mean pressure of 100.8 mm Hg in dogs that did not. Even if the findings of Angell-James and Bobik (1979) in isolated preparations in rabbits were applicable to our findings in vivo in dogs, an increase of 11% in an average discharge of 15-16 impulses/sec at 100 mm Hg would do little to alter our conclusion that aortic baroreceptors in dogs display substantial activity at normal resting arterial pressure.

Although the conclusions that can be drawn from them are very different, our results agree with those of Pelletier et al. (1972) in a number of respects. For example, the hysteresis loop of our pressure-response curve between 180 and 100 mm Hg (Fig. 5, descending limb) and the descending pressure-response curve of Pelletier et al. are virtually superimposable. The main difference concerns the pressure range over which hysteresis is present. We found that aortic baroreceptors in dogs, like those described by Angell-James (1971, 1973) in rabbits, displayed hysteresis at mean pressures below, as well as above, 100 mm Hg, so that baroreceptor threshold was significantly higher when pressure was decreasing than when it was increasing. (Such an asymmetry of the baroreceptor response at low pressures might explain the "rebound bradycardia" often seen in the experimental animal as a sequel to the baroreflex tachycardia induced by a transient reduction in arterial pressure.) Pelletier et al. (1972), on the other hand, reported that aortic baroreceptors in dogs displayed little activity at normal arterial pressures, and consequently no hysteresis below 100 mm Hg. A possible explanation of this difference is that the method of recording multifiber activity employed by Pelletier et al. (1972) did not give adequate resolution of the baroreceptor signal when pressures were low. In our experiments, as in those of Angell-James (1971, 1973), activity was recorded from "single" fibers. Although the major part of our stimulus-response curve for aortic baroreceptors in dogs is above the normal baseline pressure of 100 mm Hg, and there seems no reason to doubt that, as Pelletier et al. (1972) have shown, the curve lies to the right of that of the carotid baroreceptors, nonetheless, significant activity is present when mean aortic pressure is maintained close to the normal value. The stimulus-response curve in Figure 5 shows that directional sensitivity is an important factor in determining the magnitude of the "error signal" for small changes in pressure around the normal set-point.

In seeking explanations of the phenomenon of directional sensitivity of baroreceptors in the intact circulation, one is tempted to look for parallels in the more readily analyzed baroreceptor responses.
to controlled pressure stimuli in isolated preparations. Nevertheless, attempts to interpret directional sensitivity of the baroreceptor response in the intact circulation in terms of the mechanisms underlying the directional sensitivity of the baroreceptor response in isolated preparations must be conjectural at best. In our preparation, as in that of Pelletier et al. (1972), a relatively complex, high pressure frequency waveform supplied by the heart beat was superimposed upon a mean pressure that was varied upwards or downwards at a constant rate. In isolated vascular segments, on the other hand, relatively simple waveforms of varying amplitude and duration usually have been applied round a constant mean pressure. In experiments of the latter type (Franz, 1969; Franz et al., 1971), the overshoot and undershoot of the carotid baroreceptor response to suprathreshold square waves of pressure were both included in the general term "bidirectional rate sensitivity," and as such were held to be manifestations of the viscoelastic properties of the arterial wall. The mechanisms responsible for the phenomena of baroreceptor overshoot and undershoot in the rat aortic arch preparation have been examined in detail by Saum et al. (1976). They found that both the overshoot in discharge at the onset of a pressure square wave and its subsequent decline to a lower, steady level of activity, which together comprise the adaptation process, were due to viscoelastic wall phenomena. On the other hand, Saum et al. (1976) found that the undershoot or postexcitatory depression observed when pressure was suddenly decreased was largely the result of an electrogenic process at the nerve terminal that was blocked by ouabain. Electrogenic phenomena may account in vivo for variations of response during a single cardiac cycle, or in vitro for the undershoot observed when pressure is suddenly decreased, but their role may be less important in the circumstances of our experiments, in which cardiac variations were superimposed upon a mean pressure that was varied slowly upwards or downwards at a constant rate. In rabbits, baroreceptor hysteresis is present with successively increasing and decreasing pressure steps of relatively short duration (Angell-James, 1971, 1973), but can no longer be demonstrated if time is allowed for baroreceptors to adapt fully at each pressure step (Franz et al., 1971), suggesting that viscoelastic processes are responsible. Nevertheless, Brown et al. (1976) have evidence that baroreceptor hysteresis is still present in the rat aortic arch preparation under relatively static conditions, and participation of an electrogenic phenomenon cannot be ruled out entirely.

We have seen that the direction of the change in pressure was important in determining the sensitivity of the baroreceptor response to small perturbations in pressure around the set-point. We also found that a change in the level of baseline pressure, even when maintained for a relatively short period, had an appreciable influence on aortic baroreceptor response, so that pressure curves constructed from a higher baseline pressure lay to the right of curves constructed from a lower one. The process was reversible in the sense that curves were shifted to the right or left according to whether the lower or higher baseline was chosen for the initial set of observations on a given fiber.

This reversible, short-term phenomenon clearly differs from the long-term baroreceptor resetting of established hypertension (McCubbin et al., 1956; Angell-James, 1973, 1974), but it may have something in common with the short-term resetting that has been found to occur within 6-48 hours in rats (Krieger, 1970) or within 5-13 days in rabbits (Aars, 1968). It may be essentially the same phenomenon as the acute resetting recently demonstrated in an in vitro preparation in rats (Munch et al., 1980). The underlying process in short-term resetting, like that responsible for baroreceptor hysteresis, is probably akin to adaptation, which is believed to involve viscoelastic relaxation and "creep" of connecting structures in the arterial wall (Franz et al., 1971). A time-dependent elongation of connective tissue elements in series with the receptors may be a precursor of more permanent structural changes associated with increased aortic circumference in established hypertension (Wolinsky, 1972; Angell-James, 1973).

The rapidity with which resetting occurred in our experiments raises the possibility that the effect was produced reflexly by alterations in the sympathetic control of the smooth muscle of the aortic arch. Nevertheless, the precise role of such a reflex mechanism in the changes we observed remains unclear, for stimulation of the sympathetic supply to the arterial wall at baroreceptor sites has been reported variously as increasing and decreasing baroreceptor sensitivity (for references see: Sleight, 1975; Brown, 1980). Such sympathetic influence, if indeed it affects baroreceptor sensitivity in the appropriate direction, does not appear to be essential for the type of resetting that we have described, because recently Munch et al. (1980) have presented a preliminary account of acute resetting in the isolated aortic arch preparation of the rat in vitro.

Directional sensitivity remained a prominent feature of baroreceptor response when baseline mean pressure was set at a higher level, with the result that response curves were still steepest immediately on either side of the baseline. Directional sensitivity persists not only after moderate, short-term increases in pressure, it appears to be well preserved—even accentuated—in established hypertension when structural changes have occurred in the arterial wall (Angell-James, 1973, 1974). One may speculate, therefore, that in established hypertension this directional sensitivity acts in concert
with the resetting of the pressure response curve to stabilize pressure at its new level, and will do so as long as the receptors themselves remain intact.

In conclusion, our results draw attention to three operational features of aortic baroreceptors in vivo: their activation at normal levels of arterial pressure, their directional sensitivity, and their ability to reset in the short term. Hitherto, although some investigators have reported hypertensive resetting in a matter of a few hours or days, such resetting has been regarded as an early manifestation of an essentially pathological process. Our results suggest that resetting is not necessarily confined to the long term, but may occur within a matter of minutes. As such, it may represent an integral feature of baroreceptor operation in normal circumstances. Short-term shifts in sensitivity may accompany the marked and often sustained increases in arterial pressure that occur commonly in the course of normal daily activity, in response to muscular exercise or to changes in emotional state (Brod et al., 1959). Because they are most sensitive to small pressure changes on either side of the set-point, and remain so whether the set-point is normal or elevated, aortic baroreceptors with myelinated fibers are well suited to oppose oscillations in arterial pressure—the set-point itself, however, being subordinate to other more complex mechanisms of control.

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References

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