Nonlinearities of the Human Carotid Baroreceptor-Cardiac Reflex

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SUMMARY Carotid baroreceptors of nine healthy young men and women were stretched or compressed with neck suction or pressure, before and after β-adrenergic and cholinergic blockade, to evaluate several nonlinearities of sinus node baroreflex responses. Sinus node inhibition was related linearly to the intensity of brief baroreceptor stimuli over a range extending from carotid-distending pressures of about 101 ± 5 (mean ± SE) to 160 ± 6 mm Hg (the subjects' average systolic pressure was 108 ± 2 mm Hg). Sinus node responses to sustained (5 seconds) neck suction or pressure were strikingly asymmetrical. Responses were abolished by atropine, or by atropine and propranolol. Propranolol alone augmented sinus node responses to both neck suction and pressure. These results suggest that, in normal human subjects, sinuses node responses to abrupt alterations of afferent baroreceptor traffic are nonlinear and are mediated by fluctuations of efferent cholinergic activity. Most of the observed nonlinear behavior of the integrated reflex can be explained on the basis of known properties of afferent and central portions of the baroreflex arc. Circ Res 47: 208-216, 1980

HUMAN sinus node responses to fluctuations of afferent arterial baroreceptor traffic are highly nonlinear. Identical baroreceptor stimuli begun at different times within the cardiac (Eckberg, 1976) or respiratory (Eckberg and Orshan, 1977) cycles elicit strikingly different responses. These nonlinearities probably result from mechanisms operating within the sinus node and the central nervous system.

Other nonlinearities have been described. Sinus node responses are not linearly related to stimulus intensity: when carotid baroreceptors are stretched with neck suction, the level of sinus node inhibition becomes maximal at submaximal stimulus intensities (Eckberg, 1977). Sinus node responses are greater when arterial pressure rises than when it falls (Pickering et al., 1972). Cardiac slowing, provoked by rising arterial pressure, appears to be mediated exclusively by increased cholinergic activity, but cardioacceleration, provoked by falling arterial pressure, appears to be mediated by increased β-adrenergic activity as well as reduced cholinergic activity (Glick and Braunwald, 1965; Robinson et al., 1966). Finally, there are nonlinearities of human baroreflex sinus node responses which cannot be explained on the basis of extant experimental data. For example, identical baroreflex stimuli begun at identical times in the cardiac and respiratory cycles may provoke strikingly dissimilar sinus node responses (Eckberg, unpublished).

I undertook this research to answer several questions regarding human carotid baroreceptor-cardiac reflex physiology. First, the relationship between arterial pressure and pulse interval can be described by a sigmoidal function, with threshold, linear, and saturation ranges (Koch, 1931). I therefore asked whether this relationship could be delineated in volunteers, and if so, on what portion of the sigmoidal function do human subjects usually operate? Second, do reductions of arterial pressure provoke smaller responses than elevations of arterial pressure because they fall on a less steep portion of the carotid baroreceptor stimulus-sinus node response relation? Third, carotid baroreceptor stimulation with neck suction is highly unphysiological: increased carotid baroreceptor activity provokes reflex aortic hypotension, and this leads to directionally opposite changes of aortic baroreceptor activity. To what extent might aortic baroreflex adjustments modify sinus node responses to experimentally altered carotid baroreceptor activity? Fourth, does β-adrenergic stimulation contribute to cardioacceleration provoked by brief reductions of afferent baroreceptor activity? Fifth, is there any way to quantify and otherwise categorize deviant, or unpredictable, human sinus node responses to altered levels of afferent baroreceptor traffic?

Methods

Carotid baroreceptor afferent activity of nine healthy young adults was altered with neck suction or pressure before and after β-adrenergic and cholinergic blockade, and changes of atrial cycle length were measured.

Subjects

Eight men and one woman were studied three or four times over a 7-month period. They were selected from a pool of volunteers comprising about...
25 university students. The average age of volunteers (±SE) was 24 ± 1 (range 21–26) years. All were normotensive and healthy and none were taking medications. All exercised regularly; two were long distance runners. This research was approved by the Medical College of Virginia Committee on the Conduct of Human Research and all subjects gave their written consent to participate prior to the first study.

**Measurements**

Studies were conducted with subjects supine in a quiet darkened room. An ink-writing recorder was used to transcribe the electrocardiogram, beat-by-beat pulse interval, respirations (measured with a pneumograph), and neck chamber pressure (measured with a strain gauge pressure transducer mounted upon the neck chamber). In six volunteers, brachial arterial pressure was measured with a strain gauge pressure transducer connected via a saline filled tube to a plastic (0.56-mm internal diameter) catheter. In other studies, blood pressure was measured with a standard sphygmomanometer cuff while subjects were supine.

**Baroreceptor Stimuli**

Subjects wore a neck chamber (Eckberg et al., 1975) made of sheet lead and rimmed with synthetic foam rubber. Two solenoid-actuated pneumatic valves were mounted on or near the chamber; these were connected to either a constant vacuum or a constant pressure source. Valve rotation to initiate neck suction or neck pressure was timed electronically. Two patterns of pressure change were used.

**Sustained Stimuli**

Neck chamber pressure was changed abruptly (rate of pressure change, ± 2000–2500 mm Hg/sec; time to 95% of pressure change, about 25 msec) at random times within the cardiac cycle, for 5 seconds. Pressure was increased to 15 or 30, and decreased to −30 mm Hg (in random sequence). Changes of successive pulse intervals from the control pulse interval were measured for 10 seconds after the onset of the pressure change. Each pressure change was delivered about 30 times, and a composite response curve was drawn from average pulse interval changes measured during each 0.375-second period (Fig. 1). All measurements were made during held expiration, when the pulse interval is otherwise nearly constant (Eckberg, 1976).

**Brief Stimuli**

Brief baroreceptor stimuli were superimposed on a lowered baseline carotid transmural pressure to measure the entire range of the carotid sinus stimulus intensity-sinus node response relationship. To obtain these measurements, neck chamber pressure was increased abruptly to 40 mm Hg at random times within the cardiac cycle. After about 3–4 seconds had elapsed (and the pulse interval had stabilized at a new, lower level), neck chamber pressure was reduced abruptly, for 0.6 second, and then returned to 40 mm Hg. This experimental sequence is illustrated in Figure 2. Ten mm Hg decrements were used; the smallest brief pressure reduction was 10 mm Hg (from 40 to 30 mm Hg), and the largest was 110 mm Hg (from 40 to −70 mm Hg). Seven stimuli were applied at each of these, and intermediate levels, in a random sequence. Neck chamber pressure during the brief stimulus was subtracted from systolic arterial pressure to obtain an estimate of carotid transmural pressure. For example, a −40 mm Hg stimulus applied to a volunteer whose systolic arterial pres-

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**Figure 1** All pulse interval responses of one subject to 41 applications of 30 mm Hg neck pressure for 5 seconds. Each P-P interval change is plotted as a function of the interval between the onset of neck pressure (time 0) and the P wave concluding the cycle. The trend of responses is clear; however, several points in the lower right quadrant deviate considerably from the trend.

**Figure 2** Experimental record from one volunteer to illustrate the method used to superimpose brief periods of carotid stretch on reduced carotid transmural pressure. The response to the stimulus shown on the left was much greater than the response to the stimulus shown on the right, even though the timing of the two stimuli within the cardiac cycle was nearly identical.
sure was 110 mm Hg would increase the carotid
distending pressure to 150 mm Hg (110 - [-40] =
150 mm Hg).

Brief reductions of neck chamber pressure were
timed electronically to occur 0.75 to 0.85 second
before the anticipated occurrence of the next P
wave, as described in detail earlier (Eckberg, 1977).
(When the heart rate is constant, the timing of the
next P wave can be predicted from the last P-P
interval; an earlier study (Eckberg, 1976) showed
that carotid baroreceptor stimuli begun about 0.8
second before the anticipated occurrence of the
next P wave will maximally delay that P wave).

Data Reduction

Intraarterial pressure measurements were read
directly from the analog recorder output. The re-
corder amplifier gain was adjusted so that a pres-
sure change of 2 mm Hg would cause a pen deflec-
tion of 1 mm. Thus, arterial pressure measurements
were accurate to about 1 mm Hg.

Pulse interval changes were analyzed in real time
by an on-line digital computer. Several measure-
ments and calculations were printed after each neck
chamber stimulus. The last P-P interval completed
prior to the onset of the stimulus was considered to
be the control interval. In experiments employing
sustained baroreceptor stimuli, all P-P interval
changes from the control interval, and stimulus to
P wave intervals during the 10 seconds following
the onset of the stimulus were printed. In experi-
ments employing brief baroreflex stimuli, the
change of the first P-P interval concluded after the
onset of the stimulus from the control interval was
printed.

There were two square wave inputs to the com-
puter generated by neck chamber pressure or elec-
trocardiogram threshold crossings. The neck cham-
ber threshold was set about 5 mm Hg above or
below the baseline pressure (sustained stimuli), or
at 35 mm Hg (brief stimuli). The electrocardiogram
threshold was set on the descending portion of the
R wave. The time from the onset of the preceding
P wave until the R wave threshold crossing was
subtracted from the measured stimulus to R wave
interval to obtain the stimulus to P wave interval.
The PR interval did not change importantly during
these studies; therefore, RR intervals equaled PP
(or “pulse”) intervals, and are referred to as such in
this manuscript.

Drugs

In five subjects, dl-propranolol, 0.2 mg/kg, was
infused intravenously after responses to sustained
neck suction or pressure had been measured. Mea-
surements were repeated; atropine sulfate, 0.04 mg/
kg, then was given intravenously and a third set of
measurements was obtained. The average time
from the onset of propranolol infusion until the last
post atropine measurement was 87 ± 5 minutes. In
one subject, the sequence of drug administration
was reversed.

Statistical Analysis

Statistical comparisons were made with the
paired and unpaired t-tests and least squares linear
regression (Winer, 1962) and an analysis of variance
(Satterthwaite, 1946). Differences were considered
significant when $P < 0.05$.

I also used a statistical technique (Eckberg, 1979)
to estimate objectively the pressures (threshold and
saturation) at which the stimulus-response relation-
ship departed from steep linearity. Least squares
linear regression analyses were performed for the
six carotid distending pressures to the left (to de-
termine threshold) or right (to determine satu-
ration) of the stimulus-response relationship (Figs. 3
and 4). An arbitrary threshold (or saturation) pres-
sure was chosen, and a computer program calcu-
lated the residual sum of squares for portions of the
intensity-response relation lying to the left and to
the right of this point. An iterative program shifted
this pressure by increments or decrements of 1 mm
Hg, and calculations were repeated. The pressure
at which the residual sum of squares was least was
taken as the threshold (or saturation) pressure.

Results

Sustained Stimuli

All responses of one volunteer to 41 applications
of 30 mm Hg neck pressure for 5 seconds are de-

![Figure 3](http://circres.ahajournals.org/)

**Figure 3** All responses of the same volunteer whose
record was depicted in Figure 2 to brief neck suction
superimposed on neck pressure of 40 mm Hg. Average
responses at each level are indicated by unfilled circles.
Carotid-distending pressure was considered to be the
systolic arterial pressure less the lowest pressure during
the brief stimulus. The broken line indicates this sub-
ject's systolic arterial pressure. The stippled area indi-
cates the standard deviation of responses.
BAROREFLEX MODULATION OF SINUS NODE FUNCTION/Eckberg

Figure 4 Average responses of all nine subjects to brief baroreceptor stimuli superimposed on sustained neck pressure of 40 mm Hg. Calculated threshold pressures were aligned and average responses at each level were calculated. The number of subjects whose data fell at the extremes of the stimulus-response relationship are indicated in parentheses. Brackets encompass 1 se. Stippled area = SD.

Picted in Figure 1. Pulse interval shortening (cardioacceleration) began within the 1st second and reached a constant level between 2 and 3 seconds after the onset of the stimulus. During the 5 seconds after neck chamber pressure returned to normal (between 5 and 10 seconds on the graph), the pulse interval rose abruptly to levels considerably above the control level and then decayed toward the baseline. The trend of these responses is unmistakable; however, the variance about the mean response is considerable. Moreover, several responses (lower right quadrant of the graph) deviated from the trend in a manner which could not have been predicted from knowledge of the usual pattern.

Average responses of all nine volunteers to sustained neck pressure and suction are shown in Figure 5 (the stippled area indicates the standard deviation of responses). Responses were integrated during the first 5 seconds after the onset of stimuli. The response to 30 mm Hg neck pressure was 2.0 times as great as that to 15 mm Hg neck pressure, and only 0.43 times as great as the response to 30 mm Hg neck suction. The patterns of responses to neck suction and pressure were also strikingly asymmetrical. The peak response to neck suction occurred between 1 and 2 seconds, whereas the peak response to neck pressure appeared between 3 and 4 seconds. Between 4.5 and 5.0 seconds after the onset of sustained stimuli, the average pulse interval response to neck suction was greater than that to neck pressure (122 ± 25 vs 87 ± 12 msec), but this difference was not significant (P = 0.22). The greatest standard deviation of responses to neck suction occurred with the peak responses; the greatest standard deviation of responses to neck pressure occurred after neck chamber pressure was restored from 30 mm Hg to ambient levels.

Responses during the first 1.2 seconds of 30 mm Hg neck suction or pressure are shown on expanded scales in Figure 6. The latencies between the onset of the stimuli and the onset of the responses were estimated using the statistical technique described under Methods (Eckberg, 1979). Average pulse interval prolongation with carotid stretch began at 0.26 second; pulse interval shortening with carotid compression began at 0.44 second. The rate of pulse interval change was greater after neck suction than after neck pressure (Fig. 6, inset); the slope during neck suction was 0.139 (msec pulse interval prolongation/msec) and the slope during neck pressure was −0.079.

Brief Stimuli

Figure 2 illustrates the method used to superimpose a brief baroreflex stimulus upon a reduced baseline carotid transmural pressure. Each brief stimulus was applied at about the same time in the cardiac cycle; however, the response shown in the left panel was much greater than that shown in the right panel. Both stimuli were applied during held expiration. All responses of the same volunteer to all brief stimuli are shown in Figure 3. Carotid distending pressures of 100 mm Hg (this volunteer's systolic pressure) and below did not provoke pulse interval prolongation, and pressures 150 mm Hg or greater elicited maximal responses. Sinus node responses in the “linear range” were highly variable.
Intraarterial Pressure Changes during Neck Suction

Systolic arterial pressure rose slightly (by 4.8 ± 0.9 mm Hg) during 10 seconds of held expiration without neck suction (filled circles, upper panel, Fig. 7). Systolic pressure during neck suction (unfilled circles) became significantly \((P = 0.011)\) lower than control pressure between 2 and 3 seconds, and declined at an initial rate (during 0 to 4 seconds) of 1.78 mm Hg/sec \((r = 0.79)\), or 0.06 mm Hg/sec per mm Hg neck suction \((1.78/30)\). Diastolic pressure (lower panel, Fig. 7) declined (from a control level of 72 ± 1 mm Hg) at a rate of 2.33 mm Hg/sec \((r = 0.74)\).

Responses to Autonomic Blocking Drugs

Average responses of five subjects before and after propranolol, or propranolol and atropine, are shown in Figure 8. Pulse interval prolongation provoked by neck suction (left panel) was much greater after (unfilled circles) than before (filled circles) propranolol \((P = 0.001)\). The minor pulse interval shortening following the period of inhibition was not altered significantly by propranolol (and therefore, probably was not mediated by a \(\beta\)-adrenergic mechanism). Subsequent infusion of atropine (triangles) nearly abolished both components of the sinus node response to neck suction.

Average responses to 30 mm Hg neck pressure are shown in the right panel of Figure 8. Although average pulse interval shortening was only slightly greater after (unfilled squares) than before (filled squares) propranolol, this difference was highly significant \((P = 0.014)\). There was a striking augmentation of pulse interval prolongation after return of neck chamber pressure from 30 mm Hg to ambient pressure.

The average stimulus-response relationship for all volunteers is depicted in Figure 4. To obtain this plot, calculated threshold pressures (see Methods) were aligned and responses at each carotid distending pressure were averaged. (The stimulus-response relationship of one volunteer was linear to the smallest carotid distending pressure tested; this pressure was taken as his threshold pressure for analysis of average responses of the group.) The calculated average threshold pressure for the group was 101 ± 5, and the calculated average saturation pressure was 160 ± 6 mm Hg. The standard deviation was greatest in the linear portion of the intensity-response relationship.

These results were compared with measurements obtained earlier (Eckberg, 1979) from 10 normotensive subjects. The calculated saturation pressures and slopes of the intensity-response relation lying to the left of the saturation pressure were comparable in the two groups \((P = 0.310\) and 0.736). Thus, although the subjects studied for the present report were not consecutive volunteers, the responses of these subjects are probably representative of responses of normotensive young adults.
These findings do not exclude the possibility that adrenergic activity was augmented by upright posture. This conclusion is supported by an earlier study (Eckberg et al., 1976) in which arterial baroreceptor-cardiac responses were not diminished by ß-adrenergic blockade, even when background adrenergic activity was augmented by subsequent infusion of propranolol.

Earlier studies (Pickering et al., 1972; Eckberg et al., 1976) showed that propranolol augments baroreflex sinus node inhibition. The mechanism underlying this effect of propranolol was studied by Dorward and Korner (1978) in anesthetized rabbits. They found that propranolol enhances baroreflex-mediated reductions of renal sympathetic nerve activity, and they attributed this effect to altered central nervous system baroreflex modulation. An alternative mechanism was proposed by Angell-James and Peters (1979): they found that ß-adrenergic blockade with propranolol augments baroreflex responses through an effect on the baroreceptors themselves.

Because the carotid baroreceptor stimulus-cardiac response relationship is made steeper by propranolol (Eckberg et al., 1976), augmentation of pulse interval responses to both rising and falling arterial pressures is expected. If the baroreceptor threshold is not lowered appreciably by propranolol, augmentation of sinus node responses to carotid compression should be less than augmentation of responses to carotid stretch (because the changes of carotid transmural pressure occur over different portions of the stimulus-response relationship). Therefore, augmentation of the antihypertensive effect of propranolol on heart rate should overshadow augmentation of the antihypotensive effect. Enhancement of baroreflex responsiveness by propranolol may contribute to its antihypertensive action and also may have other important clinical implications (Reyes, 1973).

Stimulus-Response Relationship

The sigmoidal relationship between pulse interval and arterial pressure (Koch, 1931) has been divided into threshold, linear, and saturation ranges. I defined baroreceptor threshold as the carotid distending pressure at the beginning of the steep linear portion of the stimulus-response relationship (Figs. 3 and 4). Average systolic arterial pressure and calculated threshold pressure were nearly the same (108 vs. 101 mm Hg) in the nine subjects studied. Therefore, the baroreflex in these volunteers appears to operate near the lower nonlinear portion of the stimulus-response relationship.

In this manuscript, the term "threshold" is used in a restricted sense, to refer only to sinus node responses to brief carotid baroreceptor stimuli. The evidence suggests that the thresholds for brief and prolonged changes of carotid afferent activity are not the same: in all subjects, including those two

Autonomic Mediation of Baroreceptor-Cardiac Reflex Responses

In five subjects, baroreflex responses were not reduced after propranolol, but were nearly abolished by subsequent atropine administration (Fig. 8). In one subject, atropine, given before propranolol, nearly abolished sinus node responses. Therefore, early sinus node responses to increased or decreased carotid sinus afferent activity are mediated by fluctuations of efferent cholinergic activity. This conclusion is supported by an earlier study (Eckberg et al., 1976) in which arterial baroreceptor-cardiac responses were not diminished by ß-adrenergic blockade, even when background adrenergic activity was augmented by upright posture. These findings do not exclude the possibility that late cardioacceleration caused by arterial hypoten-
whose calculated thresholds lay above their average systolic arterial pressures, reduction of carotid distending pressure with sustained neck pressure provoked pulse interval shortening. This suggests that efferent vagal responses to afferent baroreceptor information are conditioned by both the intensity and the duration of baroreceptor stimuli, and that there is a complex central "threshold" which may be different from the threshold of individual baroreceptor units.

The steep linear region of the intensity-response relationship extended from about 101 ± 5 to 160 ± 6 mm Hg. Thus, in normal young adults, baroreflex heart rate adjustments appear to be most efficient within the accepted range of normal systolic pressures. The average calculated saturation pressure (defined as the carotid distending pressure beyond which further elevations of pressure did not provoke further prolongations of pulse interval) was 160 (range: 131 to 181) mm Hg.

These estimates of threshold and saturation pressures and of the extent of the linear range are based on the assumption that pressure or suction applied to the neck chamber is transmitted faithfully to the carotid sheath. If transmission of pressure changes is imperfect, as suggested by Ludbrook et al. (1976) (these workers found that neck pressure is reduced by 14% and neck suction by 36% in transmission through neck tissues), the threshold would be 100, rather than 101 mm Hg, the saturation pressure would be 141, rather than 160 mm Hg, and the linear range would be correspondingly reduced. The disparity between responses to carotid compression and stretch would be even greater than shown (the ratio of integrated responses to neck pressure and suction was only 0.43, whereas the ratio of intensities of neck pressure and suction, with the correction factors applied, was 1.34).

Asymmetry of Responses to Carotid Compression and Stretch

The latency (time from the onset of stimuli until the earliest measurable sinus node responses) was shorter with carotid stretch than with carotid compression (0.26 vs. 0.44 second, Fig. 6). The disparity of reflex latencies may reflect in part asymmetry of central nervous system processing of afferent baroreceptor information. Katona and Barnett (1969) found that increases of efferent vagal cardiac activity begin about 100 msec after sudden elevations of carotid sinus pressure, but reductions of efferent vagal cardiac activity do not begin until about 300 msec after sudden reductions of carotid sinus pressure. The difference between these response times, 200 msec, is very close to the difference between latencies found in the present study. Although the delay from the onset of stimuli until the onset of sinus node responses is longer after carotid sinus compression than after carotid sinus stretch, it is still remarkably short. Earlier estimates of the duration of this reflex latency have been in the range of 1–5 seconds (Samaan, 1935; Pickering et al., 1972).

Sinus node inhibition occurred after the abrupt return of neck chamber pressure from 30 mm Hg to ambient levels (after 5 seconds in Figs. 5 and 8). The pattern of this response was similar to that which occurred during neck suction, but the magnitude of the response (after a correction was made to allow for the different baselines) was significantly less (P = 0.006) after release of neck pressure. This disparity provides additional evidence that carotid-distending pressures below systolic pressure do not lie on the steepest portion of the stimulus-response relationship.

Arterial Pressure Response

The perturbation of autonomic function provoked by neck suction has no counterpart in nature; during this intervention, carotid baroreceptors are stretched, but shortly thereafter, aortic baroreceptors are compressed (by reflex hypotension). I measured arterial pressure during neck suction to estimate the extent to which reflex aortic hypotension might modify sinus node responses to baroreceptor stimulation with neck suction.

The latency between the onset of neck suction and the onset of hypotension in six subjects was about 2.5 seconds. In an earlier study conducted with a larger number of subjects (nine), significant reduction of systolic arterial pressure began within 1 second after the onset of the first in a series of repetitive applications of neck suction (Baskerville et al., 1979). Thus, the level of aortic baroreceptor stimulation may decline very early after the onset of neck suction. The present results (Fig. 6) also show that cardioacceleration begins very soon (within 0.5 second) after the onset of an abrupt reduction of afferent baroreceptor activity. These results suggest that aortic receptors cannot influence sinus node responses during the first 2 seconds after the onset of neck suction, may exert a small, but measurable effect during the next 2–3 seconds, and probably exert a steadily increasing, and perhaps major effect upon sinus node responses after the first 5 seconds of neck suction.

Variance of Baroreflex Responses

The standard deviation of baroreflex responses was small in the threshold and saturation regions of the stimulus-response relationship, and large in the linear portion (stippled areas, Fig. 3 and 4). Since baroreceptor responses to abrupt changes of carotid sinus pressure are highly deterministic (Katona et al., 1968), and since pulse interval follows changes of efferent vagal cardiac activity in a linear manner (Katona et al., 1970; Chess and Calaresu, 1971), variance of baroreflex responses must be due primarily to factors operating within the central nervous system portion of the reflex arc.
I speculate that in conscious human subjects (but probably not in unconscious experimental animals whose central autonomic mechanisms have been distorted by general anesthesia), there is an oscillation of the level of central baroreflex suppression (or gain) that is not explained by known mechanisms. According to this construction, low levels of afferent baroreceptor traffic (near threshold) yield monotonic efferent vagal responses because, even under optimal conditions, small baroreceptor inputs yield only small vagal outputs. Similarly, high levels of baroreceptor traffic (near saturation) yield monotonic vagal responses because intense baroreceptor inputs override the capacity of central mechanisms to suppress vagal responses. Moderate levels of afferent baroreceptor traffic (linear range) yield highly variable vagal responses because, although central mechanisms can suppress vagal responses to these levels of afferent input, the degree of central suppression is variable. Obviously, under different experimental circumstances, as, for example, during exercise, central mechanisms may override afferent baroreceptor influences, however strong (Eckberg et al., 1972). I cannot determine from these data whether this putative central oscillation is periodic or aperiodic. If it is aperiodic, it may derive merely from random (to date, uncontrollable) activity of higher brain centers (Brooks et al., 1978) during experimental sessions.

Comparisons with Results from Other Studies

Other workers (Thron et al., 1967; Mancia et al., 1977) have found that, in normal humans, carotid compression with neck pressure provokes equal or greater (not less) arterial pressure and sinus node responses than carotid stretch with neck suction. I have no data regarding the symmetry of arterial pressure responses since I measured arterial pressure only during neck suction, not during neck pressure.

The apparently contradictory sinus node responses reported in these earlier studies may have arisen because the baroreceptor stimuli were different. The rate of neck chamber pressure change was low, relative to the normal maximum human arterial dP/dt [811 ± 39 mm Hg/sec in the brachial artery (Mason et al., 1964)], and to the rate of onset of the sustained stimuli I applied in the present study (maximum dP/dt: ± 2000 to 2500 mm Hg/sec). In the study of Thron and coworkers (their Figs. 2 and 3), stimuli did not reach full intensity (to − 80 mm Hg) until after about 10-15 seconds. In the study of Mancia and coworkers, stimuli began more rapidly (90% of the maximum pressure change was reached in less than 1 second), but the rate of pressure change still was probably considerably lower than that of the natural arterial baroreflex stimulus.

If a normal human being operates near the threshold region of the baroreceptor stimulus-sinus node response relationship, as my data suggest, the rate of onset of neck pressure is probably not of critical importance: with carotid compression, receptors probably merely reduce their rate of firing from a low, to a lower level, or they stop firing altogether. The rate of onset of neck suction, however, is probably of great importance in determining sinus node responses. Rate sensitive components of the receptor response (Landgren, 1952; Eckberg, 1977) may not be activated by stimuli whose onsets are slow, and afferent baroreceptor traffic, efferent vagal traffic, and pulse interval prolongation will be reduced correspondingly. Moreover, adaptation occurring during the slow onset of these stimuli also may diminish afferent and efferent responses.

My data suggest that if only "steady state" baroreceptor-cardiac reflex responses were measured (as, for example, between 4.5 and 5.0 seconds of sustained neck pressure or suction), important, early transient asymmetries will not be recognized. It is problematical whether analysis of early transients or of "steady state" responses (Korner et al., 1972) is preferable. I believe that the early transients must have some physiological significance, and that a case can be made for applying experimental stimuli that are similar to natural baroreflex stimuli. I have focused on the effects of brief neck suction because the natural arterial baroreflex stimulus is a mechanical arterial stretch which has a rapid onset and a short duration, and which provokes hemodynamic changes that last only seconds.

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