Responses of the Heart to Stimulation of Aortic Body Chemoreceptors in Dogs

F. Karim, R. Hainsworth, O.A. Sofola, and L.M. Wood

SUMMARY We stimulated the aortic chemoreceptors in dogs that were anesthetized with chloralose and artificially ventilated by perfusing the isolated aortic arch with venous blood. Inotropic responses were determined by measuring the maximum rate of change of left ventricular pressure (dP/dt max) with aortic pressure and heart rate held constant. Stimulation of the aortic chemoreceptors resulted in a decrease in heart rate of 30 ± 5 beats/min (mean ± SE) from 166 ± 7.7 beats/min and an increase in dP/dt max of 501 ± 85 mm Hg/sec from 3508 ± 154 mm Hg/sec. These changes were statistically significant (P < 0.001). The afferent pathway of the reflex was shown to be in the vagus nerves and the efferent pathway in the cardiac sympathetic nerves. In some of the dogs, the carotid chemoreceptors were also stimulated. This resulted in decreases in heart rate and dP/dt max of 48 ± 24 beats/min and 785 ± 142 mm Hg/sec. Thus we have shown that stimulation of aortic chemoreceptors evokes chronotropic and inotropic responses opposite to those evoked from stimulation of carotid chemoreceptors. Circ Res 46: 77-83, 1980

STIMULATION of the carotid body chemoreceptors, with ventilation held constant, results in reflex bradycardia (Daly and Scott, 1958) and negative inotropic responses (Hainsworth et al., 1979). However, there has been no adequate study of the effect of physiological stimulation of the aortic body chemoreceptors on the inotropic and chronotropic state of the heart. Several groups of investigators have attempted to stimulate these receptors by injection of drugs such as nicotine into the open aortic arch, but the results are inconclusive largely because of inadequate localization of the stimulus to the chemoreceptors and control of pressure to the baroreceptors (Comroe and Mortimer, 1964; Stern and Rapaport, 1967; Biro et al., 1973; Stern et al., 1964).

In the present study, by vascularly isolating the aortic arch, we were able to stimulate the chemoreceptors with venous blood. The inotropic responses were assessed by measuring the maximum rate of change of left ventricular pressure (dP/dt max) with heart rate and aortic pressure held constant (Furnival et al., 1970). In four of the experiments, we also examined the cardiac responses to stimulation of the carotid body chemoreceptors.

Methods

Dogs weighing 20-29 kg were anesthetized with chloralose (0.1 g/kg body weight, Cambrian Chemicals Ltd) infused through a catheter inserted into...
the inferior vena cava through a saphenous vein. Additional doses of chloralose (about 10 mg/kg every 15 minutes) were given to maintain a state of light surgical anesthesia. The neck was opened in the midline, the trachea was cannulated, and the dog was ventilated with positive pressure by means of a Starling "Ideal" pump using 40% oxygen in nitrogen humidified at room temperature. The rate of the pump was 18 strokes/min, and the stroke volume was approximately 17 ml/kg. When the pleura was opened, a resistance to expiration was inserted, equivalent to 3 cm H$_2$O.

The regions of both common carotid bifurcations were vascularly isolated and perfused at constant pressure, as previously described (Hainsworth and Karim, 1973, 1976). In four experiments in which we stimulated the carotid chemoreceptors, the blood was drained, through the catheters in the lingual arteries, into an external jugular vein. In the remaining experiments, blood was allowed to flow through the internal carotid arteries.

The technique for isolating the aortic arch region was similar to that described previously (Hainsworth et al., 1970; Hainsworth and Karim, 1972; Hainsworth et al., 1975; Karim et al., 1978). Briefly, the left 2nd to 5th ribs were removed to expose the aortic arch. The pericardium was opened, and strings were placed around the ascending aorta and the origins of the left subclavian and brachiocephalic arteries in preparation for aortic cannulation. The descending aorta was mobilized by cutting the upper four pairs of intercostal arteries between ties.

Two silver-ring electrodes were sewn onto the right atrial appendage for pacing. In all two but two dogs, a miniature pressure transducer (model P13, Konningsberg Instrument Inc.) was introduced into the left ventricle through the left atrial appendage and secured in place by a tie around the base of the appendage. In the remaining two dogs, a short stainless steel cannula with side holes (length = 5 cm, bore = 1.2 mm) was inserted into the left ventricle through the apical dimple, tied in place by means of a purse-string suture, and firmly clamped in position. The dogs were given heparin (Pulairin, Evans Medical Ltd., 500 IU/kg followed by 50 IU/kg every 30 minutes), and the circuit (Fig. 1) was filled with dextran solution (Dextraven 150, Fisons Pharmaceuticals Ltd.) or a mixture of dextran and blood obtained from another dog. Temporary by-passes were connected between the proximal ends of the left subclavian and a femoral artery to allow some circulation to the caudal part of the body during cannulation procedure.

The perfusion circuit (Fig. 1) was connected to the dog as follows. A curved stainless steel cannula was inserted into the aortic arch, and the arch was isolated by tightening the snare around the ascending aorta and clamping the bypass. The aortic blood passed through the aortic cannula and was distributed to the descending aorta and the aortic reservoir, from which blood was distributed to the isolated carotid sinuses, the isolated aortic arch, and the head of the dog through cannulas inserted into the distal end of the left subclavian artery and the proximal end of the left common carotid artery. The pressure of blood in the aortic cannula was maintained by the aortic reservoir in which the pressure of the air above the blood was controlled. The aortic arch was perfused at constant pressure with blood taken either from the aortic reservoir or from a cannula in the inferior vena cava. The temperature of the perfusate was maintained at 37–38°C by use of a heat exchanger. A cotton mesh filter (pore size about 220 μm) was also placed in the perfusion line between the roller pump and the aortic arch. The blood from the aortic arch drained from a cannula (bore = 2 mm) tied in the brachi-
occhial artery and was returned to an external jugular vein. Samples of blood were withdrawn from the outflow cannula to measure the Po2, Pco2, and pH of blood perfusing the arch using a blood gas electrode system (Corning, model 165). In some experiments, the blood passed through an oxygen electrode system (Electronic Instruments Ltd.). The output from the amplifier for the left ventricular pressure at lower sensitivity (20 mm Hg = 10-mm paper); (2) through a variable series resistance to a galvanometer to measure left ventricular pressure at lower sensitivity (20 mm Hg = 10-mm paper); (3) to an analogue differentiator to provide a signal of dP/dt which was amplified and recorded; and (4) to a digital cardi otachometer (Gilford Instruments Inc.) to record ventricular rate. The differentiator was calibrated such that inotropic responses to perfusion of the carotid bodies with venous blood with the carotid and aortic pressures held constant. The values reported are means ± SE of the mean. Significance was determined by paired t-test.

Results

Po2, Pco2, and pH of Perfusate

The values of Po2, Pco2, and pH of the arterial perfusate were 105 ± 3.0 mm Hg, 39 ± 0.22 mm Hg, and 7.37 ± 0.001 units, respectively. The corresponding values for the venous perfusate were 31 ± 1.0 mm Hg, 54 ± 1.0 mm Hg, and 7.28 ± 0.004 units.

Responses to Perfusion of the Aortic Arch with Venous Blood

During arterial perfusion, in 19 tests in 11 dogs, the values of the variables measured were as follows: aortic arch perfusion pressure, 151 ± 9.0 mm Hg; carotid sinus pressure, 124 ± 7.5 mm Hg; systemic arterial pressure, 111 ± 4.5 mm Hg; heart rate (when not paced), 166 ± 7.7 beats/min (results from 10 dogs only); left ventricular end-diastolic pressure (in four dogs measured), 5.8 ± 1.13 mm Hg; left
ventricular systolic pressure, 154 ± 5.2 mm Hg; and left ventricular dP/dt max, 3508 ± 154 mm Hg/sec.

With the heart not paced, perfusion of the aortic arch with venous blood resulted in an increase in heart rate of 13.6 ± 2.0 beats/min (8.2 ± 1.2%). This response was statistically significant (P < 0.001). The average values of heart rate from each dog, during perfusion of the aortic arch with arterial and venous blood, are listed in Table 1. Figure 2A shows an example of the responses obtained.

With the heart paced at 200 ± 4 beats/min, perfusion of the aortic arch with venous blood resulted in an increase in dP/dt max of 501 ± 85 mm Hg/sec (14.0 ± 2.1%; P < 0.001). Left ventricular systolic pressure increased by 3.4 ± 1.7 mm Hg (P > 0.05), and left ventricular end-diastolic pressure decreased by 1.03 ± 0.6 mm Hg (P > 0.05). The average values of dP/dt max obtained from each dog during pacing are given in Table 1, and an example of experimental records is shown in Figure 2B.

Responses to Perfusion of the Aortic Arch with Venous Blood at Pressures below Threshold for Baroreceptors

In five dogs, we increased aortic pressure in steps of about 20 mm Hg to determine the lowest pressure that resulted in reflex changes in heart rate and dP/dt max. Values between 120 and 140 mm Hg were obtained as the threshold for baroreceptors. These values are similar to those reported previously (Hainsworth et al., 1970; Hainsworth and Karim, 1972). The effects then were determined of perfusing the aortic arch with venous blood with the perfusion pressure held below this level. Heart rate, measured in two of the dogs, increased by 12 beats/min from 180 and 179 beats/min; dP/dt max, in all five dogs when the heart was paced, increased by 383 ± 79 mm Hg/sec from 3637 ± 195 mm Hg (+10.5 ± 1.8%). These responses were not significantly different from those obtained at higher aortic arch perfusion pressures.

Effect of Section or Cold Blockade of the Vagus Nerves

In one dog both cervical vagosympathetic trunks were cut, and in another they were cooled to a surface temperature of 8°C by a thermoelectric module (De La Rue Frigistor Ltd.). Before the nerves were cut, perfusion of the aortic arch with venous blood resulted in an increase in dP/dt max (heart paced) of 375 mm Hg/sec from 3435 mm Hg/sec. No response was obtained after the nerves were cut. In the other dog before the nerves were cooled,
dP/dt max increased by 323 mm Hg/sec from 2910 mm Hg/sec. When the nerves were cooled, venous perfusion of the aortic arch increased dP/dt max by only 92 mm Hg/sec from 2490 mm Hg/sec.

**Effect of Crushing or Blocking Efferent Sympathetic Nerves**

In one dog both ansae subclaviae were crushed, and in another the efferent sympathetic nerves to the heart were blocked by intravenous propranolol (0.5 mg/kg). The responses of heart rate and dP/dt max to venous perfusion of the aortic arch before crushing the ansae were +6 beats/min and +600 mm Hg/sec and before giving propranolol +20 beats/min and +293 mm Hg/sec. After crushing the ansae or giving propranolol, no responses of either heart rate or dP/dt max were obtained.

**Comparison of the Cardiac Responses to Venous Perfusion of the Aortic Arch and Carotid Bifurcations in the Same Dog**

In four dogs, perfusion of the isolated carotid bifurcations with venous blood resulted in a decrease in heart rate of 48 ± 24 beats/min from 147 ± 20 beats/min (−31.3 ± 13.7%) and a decrease in dP/dt max of 795 ± 144 mm Hg/sec from 3824 ± 295 mm Hg/sec (−20.6 ± 3.3%). In the same preparations, perfusion of the aortic arch with venous blood resulted in an increase in heart rate of 11 ± 3.1 beats/min from 157 ± 16 beats/min (+7.0 ± 2.0%) and an increase in dP/dt max of 476 ± 151 mm Hg/sec from 3630 ± 382 mm Hg/sec (+13.0 ± 3.0%). An example of the opposite inotropic responses to stimulation of the aortic and carotid chemoreceptors in the same dog is shown in Figure 3, and the averages of the values obtained from all four dogs during venous perfusion of the carotid bifurcations are listed in Table 2.

**Discussion**

Our experiments have shown that perfusion of the aortic arch with venous blood, in dogs anesthetized with chloralose, consistently results in increases in the rate and the inotropic state of the heart. The responses were abolished by cutting or cooling the vagus nerves in the neck or by crushing the cardiac sympathetic nerves or blocking their effect with propranolol. This shows that the afferent pathway for the reflex was in the vagus nerves and the efferent pathway in the cardiac sympathetic nerves. The key question to be answered is whether we can assume that the effects produced by perfusing the aortic arch with venous blood are due to stimulation of aortic chemoreceptors.

The region of the aorta that was isolated vascularly from the rest of the circulation contains most of the arteries to the chemoreceptors (Comroe, 1939; Coleridge et al., 1970). We confirmed the effectiveness of the isolation procedure in all dogs by stopping the perfusion and noting that the pressure in the isolated aortic arch fell to near venous levels. Furthermore, in four of the dogs, we determined the region perfused through the aortic segment by injection of Evans blue dye or Indian ink into the isolated arch at normal perfusion pressures and observed staining only in the region between the aorta and the pulmonary artery. No staining was seen in the coronary arteries, in the aorta proximal or distal to the isolated segment, or in the pulmonary circulation. The venous blood, therefore, would not have changed the activity of the afferent nerves in the pulmonary or coronary regions.

The only other mechanism to exclude is whether the responses may have been due to reduced activity of aortic baroreceptors during perfusion of the aortic arch with venous blood. This is unlikely because the responses to perfusion with venous blood were not different when the perfusion pressure was held below the threshold for the aortic baroreceptor reflexes (Hainsworth et al., 1970; Hainsworth and Karim, 1972). Also A.U. Kadiri, C.M. Malpus, and C. Kidd (personal communication) showed that baroreceptors, at least those at
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be localized. Nicotine has a widespread action on

the studies involving injections of drugs into the

initial increases in heart rate in most experiments

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aortic bodies perfused, which may vary from dog

were not mediated by the receptors with afferents running in the sympathetic
to acute hypoxia in the anaesthetised dog. Can J Physiol

Some of the aortic bodies receive their blood

supply from the left coronary artery (Comroe, 1939;

Coleridge et al., 1970), and these would not have

been stimulated in the present experiments. Therefore,
the responses obtained are not likely to have

been the maximum that the aortic chemoreceptors

are capable of producing. Furthermore, there was a

wide variation in both the inotropic and chronotrope responses obtained from the different dogs
(see Table 1). This variation may have been due to
variations in the levels of anesthesia; in the numbers of
aortic bodies perfused, which may vary from dog
to dog (Coleridge et al., 1970); and in the amounts of
damage caused to the chemoreceptors and their
nerves during the dissection. It is also possible that
the dissection may have caused variable degrees of
damage to some of the efferent cardiac nerves.

There have been previous investigations that
attempted to examine the cardiac responses from
aortic chemoreceptors. These have involved the
injection into the ascending aorta of substances
known to stimulate chemoreceptors. Dawes and
Comroe (1954) injected phenylbiguanide into the
aorta and noted a decrease in heart rate. Comroe
and Mortimer (1964) and Stern and Rapaport
(1967) inserted delay coils in the carotid arteries to
separate temporally the stimuli to aortic and carotid
chemoreceptors. Injections of nicotine resulted in
initial increases in heart rate in most experiments
(Comroe and Mortimer, 1964) and in the inotropic state (Stern and Rapaport, 1967). The criticism of
the studies involving injections of drugs into the
nonisolated aorta is that the site of action cannot
be localized. Nicotine has a widespread action on
many nerve endings and ganglia (e.g., Coleridge and

Coleridge, 1977). Also, when delay coils are used, it
is not possible to be certain that some of the drug
did not reach the carotid and cerebral circulations
earlier than expected via collateral vessels.

Angell-James and Daly (1969) vascularly isolated
the aortic arch and found, in two experiments, that
perfusion with venous blood slowed the rate of the atri. However, in their preparation, the ventricles
were taped firmly to a cannula and the coronary ostia were included with the aortic perfusion. It is
possible, therefore, that in the two experiments the
atrial bradycardia was due to perfusion of the sino-
atrial node with venous blood (Chiba et al., 1976).

The present report is the first in which aortic
chemoreceptors have been isolated effectively and
stimulated physiologically. The finding, in the pres-
ent experiments, that the cardiac responses from
aortic chemoreceptors were directionally opposite
to those that we recently had shown to be produced
from carotid chemoreceptors (Hainsworth et al.,
1979) was surprising. To confirm this difference, in
four of the dogs we determined responses from both
aortic and carotid chemoreceptors. We were able to
alternate repeatedly between stimulation of carotid
and aortic chemoreceptors and consistently produced opposite responses. What the significance of
the difference is, we find hard to say. Certainly the
responses from the carotid receptors were much
greater, and when both aortic and carotid chemoreceptors were stimulated simultaneously, the net
effect was bradycardia and negative inotropism.
However, we cannot be certain how much of this is
due to the fact that carotid chemoreceptors could
be isolated with relatively little dissection, whereas
the aortic receptors were more difficult. Because of
the methodological problems, we did not feel that quantitative studies of the interaction would be
very informative. It is known that vascular resistance
is increased by stimulation of either carotid or aortic chemoreceptors (Daly and Scott, 1962; Daly
et al., 1965). This implies that it is the carotid rather
than the aortic chemoreceptors that give rise to the
differential pattern of responses. Stimulation of the
carotid chemoreceptors increases the activity in the
sympathetic nerves to peripheral vessels but decreases the activity in the cardiac sympathetic nerves.
Stimulation of the aortic chemoreceptors, on the other hand, results in excitation of the sympathetic
nerves to both regions.

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<th>V</th>
<th>% Change</th>
<th>dP/dt max (mm Hg/sec) A</th>
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Values listed are averages obtained from each dog during perfusion of carotid bifurcations with arterial (A) and venous (V) blood at constant aortic arch pressure (169 ± 17 mm Hg), carotid sinus pressure (129 ± 13 mm Hg), aortic cannula pressure (111 ± 9 mm Hg). Heart rate also was held constant at 198 ± 1.5 beats/min when inotropic responses were determined.
AORTIC CHEMORECEPTORS AND THE HEART/Karim et al. 83

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