Hypoxia has been found to depress the concentration response curve of norepinephrine (NE) in isolated cat papillary muscles. To investigate the effects of hypoxia in intact hearts, a heart-lung preparation was developed and maximum left ventricular dp/dt (max dp/dt) was measured at constant heart rate, preload, and after load. Left main coronary arterial flow ($Q_e$) was measured with an electromagnetic flow probe. As arterial $P_{O_2}$ decreased from 90 mm Hg (96% saturation) to 20-25 mm Hg (40% saturation) at constant $P_{CO_2}$ and pH, no change in max dp/dt occurred and $Q_e$ increased 298%. In contrast to cat papillary muscles, the contractile responses to NE were augmented in hypoxia. The NE dose-response curves shifted to the left. No deterioration of contractility occurred after exposure to NE. In contrast, the chronotropic response was unaltered in hypoxia. Dose-response curves to isoproterenol also were shifted to the left in hypoxia, but responses to paired pacing were unchanged. The responses to NE under oxygenated conditions were unaltered by mechanically increased coronary flow or by increased coronary flow with nitroglycerin. Although the mechanisms responsible for these effects are unknown, the results suggest that hypoxia may open previously nonfunctioning vascular channels and thereby allow more extensive exposure of beta adrenergic receptors to circulating catecholamines.

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Potentiation of the Contractile Effects of Norepinephrine by Hypoxia

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ABSTRACT Hypoxia has been found to depress the concentration response curve of norepinephrine (NE) in isolated cat papillary muscles. To investigate the effects of hypoxia in intact hearts, a heart-lung preparation was developed and maximum left ventricular dp/dt (max dp/dt) was measured at constant heart rate, preload, and afterload. Left main coronary arterial flow (Qc) was measured with an electromagnetic flow probe. As arterial Po2 decreased from 90 mm Hg (96% saturation) to 20-25 mm Hg (40% saturation) at constant Po2 and pH, no change in max dp/dt occurred and Qc increased 298%. In contrast to cat papillary muscles, the contractile responses to NE were augmented in hypoxia. The NE dose-response curves shifted to the left. No deterioration of contractility occurred after exposure to NE. In contrast, the chronotropic response was unaltered in hypoxia. Dose-response curves to isoproterenol also were shifted to the left in hypoxia, but responses to paired pacing were unchanged. The responses to NE under oxygenated conditions were unaltered by mechanically increased coronary flow or by increased coronary flow with nitroglycerin. Although the mechanisms responsible for these effects are unknown, the results suggest that hypoxia may open previously nonfunctioning vascular channels and thereby allow more extensive exposure of beta adrenergic receptors to circulating catecholamines.

INTRODUCTION

The question of catecholamine administration often arises in patients who, for any of several reasons, have low oxygen saturations. Experimentally, however, it has been demonstrated that hypoxia diminishes the responsiveness of the myocardium to exogenous catecholamines (1, 2), and that deterioration of contractility can occur upon continued exposure to these agents (1). Although these results would argue against the use of catecholamines in the presence of hypoxia, the experimental data referred to above were obtained in isolated cardiac tissues perfused with solutions free of red cells. It is therefore unknown whether similar changes would have occurred if the heart were perfused with blood through an intact coronary circulation. The present study was designed to determine the influence of hypoxia on the responses to catecholamines of blood-perfused hearts. Since the induction of hypoxia elicits profound reflex responses, and since systemic hypoxemia could influence cardiac responses, an areflexic hemodynamically controlled heart-lung preparation was used for the experiments.

METHODS

26 mongrel dogs of either sex, weighing 22-26 kg, were anesthetized with sodium pentobarbital, 30 mg/kg i.v. A transverse thoracotomy was made at the fourth intercostal space with the animal on positive pressure ventilation. The left main coronary artery, descending aorta proximal to the first intercostal artery, left subclavian artery, brachiocephalic artery, and superior and inferior vena cavae were dissected free from the surrounding tissue. The azygous vein was ligated. A wide bore (5 mm) metal cannula was inserted into the apex of the left ventricle. Heparin, 100 U/kg was administered intravenously and the brachiocephalic artery was cannulated with an 18 F aortic perfusion cannula. A wide bore cannula was inserted into the right atrium through the atrial appendage. The aortic and right atrial cannulas were connected to the perfusion circuit as shown in Fig. 1. The blood was directed through tubing (8 inch i.d.) from the aortic cannula to the systemic and coronary perfusion circuits. The systemic circuit consisted of an electromagnetic flow meter, a plastic 1-liter reservoir placed 137 cm above the animal's heart, a heat exchanger maintained at 37°C by a circulating water bath, a bubble trap, and a resistance clamp. The tubing was filled with buffered saline (NaHCO3, 20 mEq/liter). The priming volume was approximately 200 ml. The systemic perfusion was started in the following

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by the arterial reservoir. Heart rate was maintained by electrically pacing the right atrium. Left ventricular pressure (LVP) was measured with a Statham P23Gb transducer (Statham Instruments, Inc., Los Angeles, Calif.) connected directly to the wide bore left ventricular cannula. LVP was differentiated electronically (dp/dt). The frequency response of the differentiating circuit was linear from 0.1 to 1200 Hz. Aortic and venous perfusion pressures, LVP at two sensitivities (0–200 mm Hg and 0–40 cm H2O) LV dp/dt, systemic (Qs) and coronary (Qc) flows were continuously recorded on an eight channel oscillograph. Lead II of the electrocardiogram was also monitored in the control experiments when no drugs were given. Maximum LV dp/dt at a constant heart rate and afterload and at a preload which changed by less than 5 mm Hg was used as an index of contractility. Agents were administered either as an intravenous injection or intracoronary infusion. After the maximum responses were obtained, dp/dt was allowed to return to and remain at base line for 5 min before additional studies. To induce hypoxic conditions the P02 of the respirator input gas was reduced from 155 to 22 mm Hg at a constant Pco2 of 37 mm Hg. Dose-response curves to norepinephrine were obtained first under control conditions and then during hypoxia. This was felt justified since we found that when two animals were maintained at 95% oxygen saturation for 90 min, the dose-response curves obtained after 15 min and 75 min were identical.

Drugs used were L-norepinephrine bitartrate monohydrate, L-isoproterenol-HCl, and nitroglycerin. The electrodes used for paired pacing were sutured to the right ventricle. The delay of the second impulse of the pair was approximately 200 msec.

RESULTS

Cardiac responses to hypoxia. Under control conditions at respirator input P02 of 155 mm Hg, the arterial saturation was 96±2% (mean±sd). Hypoxic conditions were established at an arterial saturation of 40±2%. Aortic pressure (92±6 mm Hg), systemic blood flow (1050±50 ml/min), and heart rate (120±12 beats/min) were kept constant in this preparation as previously described. In this controlled situation, hypoxia caused no significant changes in left ventricular maximum dp/dt (max dp/dt) or left ventricular end-diastolic pressure (LVEDP). Max dp/dt was 1250±40 mm Hg/sec under control (oxygenated) conditions and 1280±50 mm Hg/sec under hypoxic conditions; LVEDP was 6±3 mm Hg under control conditions and 8±4 mm Hg under hypoxic conditions. When the hearts were unpaced, induction of hypoxia was not associated with any significant changes in heart rates. Coronary flow increased markedly as hypoxia was induced, 92±14 ml/min at an arterial saturation of 95% and 298±36 ml/min at an arterial saturation of 40%. Max dp/dt and LVEDP remained constant for 90 min when no interventions were imposed.

1 Abbreviations used in this paper: LVEDP, left ventricular end-diastolic pressure; LVP, left ventricular pressure; max dp/dt, maximum left ventricular dp/dt; NE, norepinephrine; Qs, systemic blood flow; Qc, left main coronary arterial flow.
made in three animals maintained at an arterial saturation of 95% and in three animals maintained at an arterial saturation of 40%. The hematocrit was 41±3% in all animals studied and did not change during the experiment. Lead II of the electrocardiogram revealed no rhythm or conduction disturbance and no ST-T wave changes when the hypoxic conditions were established.

**Isotropic responses to intravenous norepinephrine.** Responses to increasing doses of norepinephrine were obtained in five animals under control and hypoxic conditions. The responses to each dose of norepinephrine were significantly greater in hypoxia (Fig. 2). Furthermore, the threshold doses under hypoxic conditions were lower, and the maximum responses were greater. Heart rates were maintained constant in each animal and averaged 184 beats/min.

**Intracoronary infusion of norepinephrine.** Since coronary flow increased over threefold in response to hypoxia while systemic flow was unaltered, a greater percentage of the total drug dosage would have reached the coronary circulation during hypoxia and could have influenced the results. Therefore, in four additional experiments norepinephrine (10^{-7} to 10^{-5} g/min) was infused directly into the coronary perfusion circuit. It was found that the responses to intracoronary norepinephrine also were augmented during hypoxia (Fig. 3). The responses of this preparation to hypoxia as well as the responses

![Figure 2 Dose-response curve to intravenous norepinephrine. Per cent change in maximum dp/dt is shown as a function of increasing doses of norepinephrine under control (arterial saturation 95%) and hypoxic conditions (arterial saturation 40%). n = 5.](image)

![Figure 3 Response curve to intracoronary norepinephrine infusions in control and hypoxic conditions. Max dp/dt is shown as a function of norepinephrine infusion rate. At 10^{-7} g/min there was no response under control conditions and a 30% increase in max dp/dt under hypoxic conditions.](image)

![Figure 4 Representative example of intracoronary (i.c.) norepinephrine under control (upper panels) and hypoxic conditions (lower panels).](image)
norepinephrine depicted are under the conditions of the experiment. Arterial saturation was maintained at 95% as norepinephrine was again administered. There was no change in max dp/dt when coronary flow was increased. LVEDP rose 5-7 mm Hg transiently but then returned to control levels. The mechanically-induced increase in coronary flow did not lead to a potentiation of the responses to norepinephrine (Fig. 5).

**Responses to norepinephrine with coronary flow increased by nitroglycerin.** In order to achieve a redistribution of coronary flow, nitroglycerin (0.1 mg/min intracoronary) was administered to four animals. After control responses to the intracoronary norepinephrine were obtained, nitroglycerin was infused at a rate that caused coronary flow to increase 30%. The responses to intracoronary norepinephrine were then reassessed; arterial saturation was maintained at 95%. The changes in coronary flow induced by nitroglycerin did not alter the contractile responses to norepinephrine (Fig. 5).

**Chronotropic responses to norepinephrine.** In four animals in which heart rate was not controlled, norepinephrine was administered intravenously in increasing doses from $10^{-4}$ to $10^{-3}$ g under control and hypoxic conditions. The heart rate responses to norepinephrine under control and hypoxic conditions were similar (Table I).

**Inotropic responses to isoproterenol.** Increases in max dp/dt as a function of increasing doses of isoproterenol administered intravenously in five animals are shown in

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**Diagram Description:**

**Figure 5** Response to intracoronary norepinephrine under control conditions (●), under conditions of increased coronary perfusion rate by a pump in the circuit (■), and under conditions of simultaneously infused nitroglycerin (▲). Arterial saturation was maintained at 95% throughout the experiment.

**Figure 6** Dose-response curve to intravenous isoproterenol under the same conditions depicted in Fig. 2.

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**Table I**

<table>
<thead>
<tr>
<th>Norepinephrine</th>
<th>Control 95% SAT</th>
<th>Hypoxia 40% SAT</th>
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</thead>
<tbody>
<tr>
<td>micrograms</td>
<td></td>
<td></td>
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<tr>
<td>0</td>
<td>124±6*</td>
<td>118±9</td>
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<td>182±6</td>
</tr>
<tr>
<td>10</td>
<td>188±8</td>
<td>186±4</td>
</tr>
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</table>

* Average in beats/min. n = 4 ±SD.

SAT, saturation.
Fig. 6. The responses to isoproterenol were significantly greater in hypoxia at all doses. The threshold doses were lower and the maximum responses were significantly greater.

**Responses to paired electrical stimulation.** Paired ventricular pacing was obtained under both control and hypoxic conditions in four animals. The responses to paired pacing were increases in max dp/dt and decreases of LVEDP at constant systemic flows. These responses under hypoxic conditions were not significantly different from those measured under control conditions: dp/dt increased 126±22% under hypoxic conditions and 112±18% under control conditions. A representative example is shown in Fig. 7. Under control conditions coronary flow increased 22±14 ml/min (24%) during paired pacing. However the coronary flow response to paired pacing was much larger in hypoxia increasing 64±18 ml/min (21%).

**DISCUSSION**

It previously has been shown that when norepinephrine is administered to isolated myocardial preparations perfused with solutions free of red cells, hypoxia results in decreased or absent myocardial responsiveness to norepinephrine (1, 2). It appears, however, that these results do not apply to the intact heart since hypoxia, at the level employed in the present investigation, enhanced the contractile response of the intact blood-perfused heart to catecholamines.

The opposite effects of hypoxia on the responsiveness of the intact versus isolated hearts to norepinephrine would appear to be caused, at least in part, by a limitation in the capacity of diffusion processes, in the absence of an intact coronary circulation, to transport adequate quantities of oxygen to stressed hypoxic myocardium. However, even when an intact coronary arterial tree is perfused with cell-free low-oxygen solutions, the response to inotropic agents is depressed (2). Furthermore, while contractility of the intact blood-perfused heart does not fall from control values when arterial Po2 is decreased from 87 to as low as 20 mm Hg, contractility falls substantially when Po2 of red cell-free solutions perfusing isolated myocardium is decreased from 440 to 120 mm Hg (1). Thus, it appears that the presence of hemoglobin as well as an intact coronary circulation are necessary for optimal responsiveness of the heart to an hypoxic stress. In addition the responses of hypoxic papillary muscles to paired electrical stimulation is diminished (3) which was not found in the present study.

Another possible explanation for the differences in the responses between the intact and isolated hearts is that the hypoxia-induced potentiation is related to changes in the amount and/or distribution of coronary blood flow. For example, it is possible that the large increases in coronary blood flow that occur after reduction of arterial oxygen content opens vascular channels not previously utilized, thereby exposing a greater quantity of beta receptors and myocardium to circulating norepinephrine. Although we attempted to test this hypothesis by increasing coronary flow mechanically and by infusing nitroglycerin into the coronary bed, neither of these interventions caused significant changes in the responsiveness of the heart to norepinephrine. However, the increase in coronary flow caused by the pump undoubtedly increased "non nutritive" flow, and even large doses of nitroglycerin, although probably causing a redistribution of flow (4), produced only relatively small increments in total coronary flow compared to those produced by hypoxia. These results therefore cannot be considered to rule out firmly the above hypothesis. On the other hand, the observations that hypoxia did not potentiate the contractile response of the heart to paired electrical pacing suggests that only circulating inotropic stimuli are potentiated by hypoxia. If this distinction is also true of other inotropic stimuli, it would suggest that the mechanism responsible for the enhanced contractile responses to catecholamines during hypoxia is related to an increase or redistribution of coronary flow, an alteration that in turn might increase the total quantity of myocardium exposed to circulating inotropic agents.

One alternative mechanism that might be responsible for the potentiation of myocardial responses to catecholamines during hypoxia should be considered. Inactivation of norepinephrine is dependent on intact adrenergic nerve endings and any interference with the binding or re-uptake of norepinephrine by the nerves results in an enhanced physiologic response (5). It is possible that an hypoxia-induced defect of this inactivation pathway could be responsible for the potentiated response. This is unlikely, however, since we found that hypoxia also caused potentiation of the myocardial response to isoproterenol, a catecholamine that is inactivated predominantly by a different mechanism.

* Norepinephrine in Hypoxia 2463
The responses of intact hearts to hypoxia have been determined previously (6–8). In contrast to the findings of the present investigation in which cardiac function was unimpaired at an arterial saturation of 40% (P_o2 of 20 mm Hg), cardiac failure was found to occur: (a) 16 min after reaching an arterial saturation of 40% in intact dogs which had received hexamethonium and propranolol to block the neural reflexes to hypoxia (7); (b) at an arterial saturation of 40% in two of four isolated perfused nonworking canine hearts subjected to hypoxia with constant pressure perfusions of the coronary arteries (6); (c) at a P_o2 of 32 mm Hg in autosupported cat hearts subjected to hypoxia after the CNS was excluded (8). The reasons for the relative resistance of the present model to the effects of hypoxia are unclear except that the complicating effects of systemic acidemia, homologous blood transfusions, adrenergic blocking agents, and artificial oxygenators were avoided.

In summary, we found that when intact blood-perfused hearts isolated from neurological reflexes were made hypoxic by lowering the arterial P_o2 to 20 mm Hg, an increased coronary flow occurred without changes in contractility. Under these conditions the contractile responses to norepinephrine and isoproterenol were enhanced while those to paired electrical stimulation were unchanged. It is postulated that the mechanism responsible for the enhanced responses to catecholamines might be related, at least in part, to the amount and/or distribution of coronary flow and thereby to an increased exposure of beta receptors to these agents. Whether these results are relevant to the administration of catecholamines to patients with congenital heart disease and right to left shunts, to patients with lung disease and arterial desaturation, and to patients with arterial desaturation due to left heart failure remains to be determined.

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REFERENCES