Cholinergic Intervention on Myocardial Dynamics and Metabolism in the Nonworking Dog Heart

VINCENT V. GLAVIANO, JACK M. GOLDBERG, MARIE PINDOK, DON WALLICK, AND CHRIST ARAVANIS

SUMMARY In electrically paced hearts of dogs subjected to cardiopulmonary bypass, intracoronary infusion of carbachol (1 /g/kg per min) caused, in the absence of external cardiac work, an increase in coronary blood flow (46%) and a decrease in both myocardial force of contraction (53%) and systemic perfusion pressure (20%). Pretreatment with atropine effectively blocked these responses to carbachol. Previous treatment with reserpine indicated that adrenergic and cholinergic interactions did occur, as observed from the more significant changes in these parameters in the absence of catecholamines. Compared with control, carbachol significantly lowered both myocardial extraction ratios (50-25%) and uptake of oxygen (4.2-3.1 ml/min per 100 g). The decrease in oxygen metabolism accompanied a significant increase in both myocardial extraction (6-18%) and myocardial uptake (1.3-5.2 mg/min per 100 g) of plasma triglycerides. The increase in triglyceride uptake was accompanied by a decline in intracellular triglyceride hydrolysis, as verified by more than a 2-fold increase in percent of C-tripalmitin incorporation. This change was concurrent with a 3-fold increase in intracellular triglyceride synthesis from H-sodium palmitate substrate. While triglyceride uptake increased partly because of an increase in coronary blood flow, it was postulated that carbachol decreased myocardial cyclic adenosine 3',5'-monophosphate (cyclic AMP) by a mechanism similar to that previously reported for acetylcholine and prostaglandin E2. The inhibition of intracellular lipolysis by cholinergic intervention elevates myocardial triglyceride levels, a response that is opposite to that reported for myocardial sympathetic stimulation.

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THE EFFECTS OF cholinergic substances on myocardial metabolism have been investigated extensively since Szekeres et al.1 reported that acetylcholine (ACh) prevented a fall in cardiac muscle stores of glycogen in rats exposed to hypoxia. Since this work was reported, ACh has been shown to reduce formation of cyclic adenosine 3',5'-monophosphate (cyclic AMP) in pancreate preparations of adenylate cyclase from dog hearts.2 This study was followed by the observation that ACh caused a rise of cyclic guanosine 3',5'-monophosphate (cyclic GMP) in the isolated perfused rat heart.3 One of the most significant actions of the cholinergic neurotransmitter has been its regulation of cardiac dynamics and metabolism through its interaction with adrenergic substances in heart muscle.4,6 Blukoo-Allotey et al.4 showed cholinergic-adrenergic interaction when they found that simultaneous administration of epinephrine and ACh inhibited glycogenolysis by epinephrine. Glaviano et al.5 reported that ACh antagonism of norepinephrine stimulation of lipid uptake and utilization in the intact dog heart was mediated through...
inhibition of adenylate cyclase activity.

The action of cholinergic substances on cardiac metabolism has been difficult to analyze because of the influence that a change in external cardiac work would have on cardiac consumption of metabolic substrates. Experiments were therefore undertaken to use the cardiopulmonary bypass preparation in the dog to obtain a cholinergic response to intracoronary administration of the choline ester, carbamyl-choline chloride (carbachol) in the absence of a change in cardiac work. Aside from its action as a cholinergic agent, the agonist was used in preference to ACh because of its total resistance to hydrolysis by acetylcholinesterase and nonspecific cholinesterase. The focus of the experiments centered on determining the effects of carbachol on coronary blood flow and myocardial uptake of oxygen, free fatty acids (FFA), and triglycerides in the normal heart and in hearts pretreated with the muscarinic-blocking drug atropine or with the chatecholamine-depleting drug reserpine.

Methods

Twenty-eight male mongrel dogs averaging 18 kg in weight were anesthetized with sodium pentobarbital (30 mg/kg, iv). The trachea was intubated, and positive-pressure ventilation was provided with a Harvard pump. A midsternal thoracotomy was performed, and the heart was suspended in a pericardial cradle. After administration of sodium heparin (3 mg/kg), the dog was placed on a cardiopulmonary bypass using a perfusion system that had been primed with 700–800 ml of Krebs-Ringer bicarbonate solution and 500 ml of blood from a donor dog anesthetized with sodium pentobarbital. Venous blood drained from the superior and inferior venae cavae was allowed to enter a 2-liter Travenol oxygenator bag receiving a fine stream of 100% O2. Blood from the oxygenator was returned to the dog by means of a calibrated Sarns portable roller pump after passing through a glass coil immersed in a water bath maintained at 39°C. From the heat exchanger, blood entered a cannulated right femoral artery and a left common carotid artery for perfusion of the trunk and head region, respectively. A cannula was inserted into the left subclavian artery close to the arch of the aorta for perfusion of the coronary arteries. The cannulated left subclavian artery supplied blood only to the coronary arteries, since the aorta was clamped just distal to the artery and the brachiocephalic artery was tied close to its origin from the aortic arch. To monitor total coronary inflow, a model EP 300-3/16 calibrated external flow probe was connected to a Carolina Medical Electronics flowmeter (model 501), interposed between the subclavian artery and the perfusion system. The oscillations imparted to the perfusion fluid by the Sarns pump were partly damped by an air chamber added to the coronary perfusion circuit. To drain and sample coronary venous blood, an intracardiac sucker sleeve was inserted from the right atrial appendage into the right ventricle. To ensure the complete collection of the coronary venous outflow from the right ventricle, the pulmonary artery was clamped at its origin from the right ventricle. To drain the left ventricular Thebesian flow and any blood escaping through the aortic valve, a drainage tube was inserted into the apex of of the left ventricle and connected to the oxygenator. The volume of blood drained from the left ventricle ranged from 13 to 24 ml/min. Thus, with both right and left ventricles devoid of blood and opened to atmospheric pressure, the effects of preload and afterload on cardiac dynamics were minimal and constant. To record changes in myocardial force of contraction, a Walton-Brodie strain gauge arch was sutured to the myocardium over the conus region of the right ventricle. The hearts were electrically paced with a Travenol model 808 pacemaker connected to a pair of fishhook electrodes inserted into the epicardium of the right ventricle close to the atrial-ventricular groove. The pacemaker was adjusted to maintain heart rate at 10–15 beats/min above the intrinsic rate. Systemic body perfusion pressure and coronary inflow pressures were measured with calibrated Statham P23Db transducers. These two pressure parameters, together with total coronary outflow, right ventricular contractile force, and a limb lead electrocardiogram, were recorded on a direct writing 8-channel Beckman model RM dynograph.

To determine whether a minimal dose of carbachol could stimulate cardiac metabolism in the absence of gross changes in peripheral vascular resistance, the metabolic effects produced by doses of carbachol ranging from 0.5 to 1.2 μg/kg per min were studied in pilot experiments. It was found that administration of 1 μg/kg per min consistently produced an increase in myocardial triglyceride uptake and a decrease in myocardial oxygen uptake. These metabolic changes were found to occur in the absence of an overwhelming decrease in peripheral vascular resistance. A total of 28 dogs were used in this study. In the first group made up of eight dogs, carbachol, (1 μg/kg per min) (Sigma) was infused into the coronary perfusion circuit for 6 minutes. All drug infusions into the coronary circulation were made with a model 940 Harvard constant infusion pump. The second group (six dogs) was infused with carbachol 5 minutes after a blocking dose of atropine sulfate (1 mg/kg) had been administered. To eliminate a possible interaction between the release of norepinephrine by adrenergic nerve endings and carbachol, a third group made up of three dogs was pretreated with reserpine (Serpasil) to deplete cardiac catecholamines. The dogs that were reserpinized received an intramuscular injection of 0.3 mg/kg per day for 2 days, followed by an additional 0.5 mg/kg injected on the day of the experiment after induction of anesthesia. The effectiveness of reserpine treatment in depleting cardiac catecholamines was tested by the absence of a change in heart rate or right ventricular contractile force during supramaximal electrical stimulation of the right stellate ganglion. In a fourth group, consisting of 11 dogs, a radioisotope study was conducted on the cardiac uptake of FFA and triglycerides.

After the dogs had been placed on total cardiopulmonary bypass and stabilized with ventricular pacing for approximately 10 minutes, with the exception of the bypass dogs receiving radioactive isotopes, control blood samples were simultaneously drawn from the femoral artery and right ventricle. At the end of the 6-minute period of carbachol infusion and with the infusion continuing, another set of arterial and coronary venous blood samples was drawn. Blood samples were analyzed for oxygen content, plasma FFA, and plasma triglycerides. The arterial-
coronary venous difference and substrate uptake by the heart were calculated for the control period and at the end of the carbachol infusion. The extraction by the heart of a metabolic substrate from plasma was measured as the myocardial extraction ratio in which, the ratio, expressed as percent, was calculated by dividing the arterial-coronary venous venous difference blood difference by the arterial level and multiplying by 100. The extraction ratio would therefore express the percent of the substrate extracted by the heart from the total concentration present in arterial blood entering the heart. The myocardial uptake of a substrate expressed in milliliters or μEq/min per 100 g of cardiac muscle was determined from the product of the myocardial arterial-coronary venous difference and coronary blood flow.9 Oxygen content of anaerobically drawn blood samples was measured in duplicate by the microgasometric method of Roughton and Scholander.10 Plasma FFA levels were determined in duplicate samples by titration according to the method of Dole and Meinertz,11 as modified by Goss and Lein.12 Plasma triglycerides were measured with a triglyceride kit (Boehringer Mannheim Corp.) that uses saponification of triglycerides with alcoholic KOH. The amount of nicotinamide adenine dinucleotide consumed was equated to the amount of glycerol liberated from the triglycerides.

In the radioisotope study, dogs on cardiopulmonary bypass were infused by coronary route simultaneously with [3H]palmitic acid and [14C]tripalmitin. Five mCi of [9,10-3H]palmitic acid sodium salt was sonified in 25 ml of a 3.7% albumin-0.9% NaCl solution, while 1 mCi of [carboxyl-14C]tripalmitin was sonified in 10 ml of 3.7% albumin-0.9% NaCl solution. The [3H]-FFA solution was divided into equal 1-ml portions and the [14C]-tripalmitin was divided into equal 0.7-ml portions which were sealed and stored at —20°C. For each experiment, one portion of both [3H]-FFA and [14C]-tripalmitin was thawed, combined in a single test tube, and brought to a final volume of 8 ml with 0.9% NaCl solution. The radioisotope solution was transfused to a syringe and infused into the coronary circulation at the rate of 1 ml/min for 6 minutes with a constant infusion pump; this represented a total dose of 150 μCi of [3H]-FFA and 50 μCi of [14C]-tripalmitin. Six of the 11 dogs infused with isotopic substrates had already had a 6-minute infusion of carbachol which was allowed to continue until completion of the isotope infusion. At the end of the perfusion period, the entire left ventricular wall was excised and placed in ice-cold Krebs-Ringer bicarbonate solution. The tissue was taken immediately to an adjacent cold room (4°C), and frozen in liquid nitrogen after major blood vessels and fat had been removed. The frozen ventricle was homogenized at 0°C in the lipid extraction mixture of Dole and Meinertz.13 Samples of the supernatant fluid were prepared and separated on thin layer chromatographic plates as previously described.19 The FFA and triglyceride areas were identified from a comparison with standards, eluted into a scintillation vial, and reduced to dryness under a stream of N2. Twenty ml of a scintillator containing 5.5 g of 2,5-diphenyloxazole and 0.05 g of 1,4-bis-[2-(4-methyl-5-phenyloxazolyl)]benzene per liter of toluene were added and the contents of the vials were counted in a Packard Tri-Carb series 314-E liquid scintillation spectrometer. Counts were corrected for channel cross-over and efficiency. The data were expressed as the percent of total activity of FFA and triglycerides incorporated into 100 g of left ventricular muscle.

Metabolic and hemodynamic changes were analyzed as paired experiments between control or pretreated controls with atropine or reserpine and carbachol administration. Differences in the percent activity of radioactive isotopes incorporated by the heart between control dogs and dogs pretreated with carbachol were determined by unpaired analysis. Levels of significance for paired and unpaired groups were determined by Student's t-test.

Results

The hemodynamic changes in an original recording from a dog on cardiopulmonary bypass and given an intracoronary infusion of carbachol for 6 minutes are shown in Figure 1. With the heart electrically paced at 200 beats/min before and during the infusion of carbachol, the mean systemic and mean coronary perfusion pressures underwent a step-wise decrease from 100 to 90 mm Hg and from 90 to 75 mm Hg, respectively. In this experiment, the head and trunk were perfused at 800 ml/min while the coronary vessels were perfused at 90 ml/min. Thirty seconds after the onset of carbachol infusion, there was a gradual decrease in right ventricular force of contraction that was accompanied by a significant increase in coronary blood flow. As the infusion was continued, ventricular force of contraction stabilized at 55% of control, while the initial increase in coronary blood flow to 145 ml/min was followed by a moderate decrease (115 ml/min), although remaining at a level higher than control for the duration of the infusion. The average changes in mean systemic blood pressure, mean coronary perfusion pressure, coronary blood flow, and myocardial force of contraction after 6 minutes of carbachol infusion in eight dogs are summarized in Figure 2. By altering peripheral vascular resistance, carbachol produced a significant decrease in systemic blood pressure (111 ± 4 to 89 ± 5 mm Hg, P < 0.001) that was accompanied by an average decrease in myocardial force of contraction of 53 ± 4% (P < 0.001). Since the perfusion pump output was constant, vasodila-

![Figure 1](http://circres.ahajournals.org/doi/fig/10.1161/01.CIR.41.4.510) An original recording representative of the effects of carbachol (1 μg/kg per min) by intracoronary route on systemic and coronary perfusion pressure, right ventricular force, coronary flow, and lead II of the electrocardiogram (ECG). The heart was electrically paced at 200 beats/min.
Atropine

Carbachol

inject to a cardiopulmonary bypass. Vertical line on top of bars indicates the standard error of the mean.

FIGURE 2  Mean changes in systemic perfusion pressure (SP), coronary perfusion pressure (CPP), coronary blood flow (CBF), and percent change in cardiac force (CF) before and after 6 minutes of intracoronary infusion of carbachol in eight dogs subjected to a cardiopulmonary bypass. Vertical line on top of bars indicates the standard error of the mean.

Table 1 summarizes the effects on cardiac extraction ratio and uptake of oxygen and plasma lipid substrates caused by carbachol infusion. The decline in cardiac force of contraction, which can serve as a qualitative measure of contractility in the absence of changes in preload and afterload, was accompanied by a significant decrease in myocardial oxygen uptake from 4.2 ± 0.3 to 3.1 ± 0.2 (P < 0.001). This change supports the findings of other laboratories concerning the dependence of myocardial oxygen consumption on contractility.14 The decrease in oxygen metabolism was observed to occur in the absence of a change in the myocardial extraction ratio of FFA. Despite the action of carbachol in causing a rise in coronary flow, cardiac uptake of FFA was not altered from that of control. On the other hand, there was a marked increase in the myocardial extraction (P < 0.01) and uptake of blood triglycerides (P < 0.05). Although arterial plasma levels of triglycerides remained unchanged (Table 2), the extraction ratio increased 3-fold during carbachol administration indicating that augmented uptake of triglycerides was due to factors other than the increase in coronary blood flow.

Acetylcholine administered by the intracoronary route generally has been assumed to increase coronary flow by its action on coronary muscarinic receptors.15 To determine if the increase in coronary flow caused by carbachol was due to factors other than stimulation of coronary muscarinic receptors, experiments were performed on six dogs that had been treated with atropine sulfate (1 mg/kg) 5 minutes prior to the infusion of carbachol. An example of the hemodynamic responses recorded from one of these six dogs during carbachol infusion is shown in Figure 3. Atropine alone had minimal effects on systemic arterial pressure, mean coronary perfusion pressure, ventricular force, and coronary flow. Subsequent carbachol infusion decreased mean systemic pressure by less than 5 mm Hg.

Table 2  Arterial Levels of Oxygen, Plasma Free Fatty Acids (FFA), and Triglyceride in Response to Carbamylcholine Chloride (Carbachol) before and after Muscarinic Blockade with Atropine

<table>
<thead>
<tr>
<th></th>
<th>Oxygen (ml/100 ml)</th>
<th>FFA (μEq/liter)</th>
<th>Triglycerides (mg/100 ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbachol</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>15.9 ± 0.4</td>
<td>499 ± 30</td>
<td>42 ± 5</td>
</tr>
<tr>
<td>Carbachol</td>
<td>15.8 ± 0.7</td>
<td>467 ± 38</td>
<td>40 ± 3</td>
</tr>
<tr>
<td>Atropine</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>15.1 ± 0.9</td>
<td>571 ± 52</td>
<td>43 ± 4</td>
</tr>
<tr>
<td>Atropine</td>
<td>15.4 ± 1.1</td>
<td>530 ± 56</td>
<td>43 ± 4</td>
</tr>
<tr>
<td>Carbachol</td>
<td>15.3 ± 1.0</td>
<td>502 ± 33</td>
<td>46 ± 8</td>
</tr>
</tbody>
</table>

Results are expressed as mean ± se. Carbachol was infused at a rate of 1 μg/kg per min for 6 minutes; n = eight dogs. Atropine (1 mg/kg) was administered 5 minutes before carbachol infusion; n = six dogs.

Table 1  Alterations in Myocardial Extraction Ratio (ER) and Uptake (U) of Oxygen, Free Fatty Acids (FFA), and Triglycerides

<table>
<thead>
<tr>
<th></th>
<th>Oxygen</th>
<th>FFA</th>
<th>Triglycerides</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ER (%)</td>
<td>U</td>
<td>ER (%)</td>
</tr>
<tr>
<td>Carbachol</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>50 ± 2</td>
<td>4.2 ± 0.3</td>
<td>11 ± 1</td>
</tr>
<tr>
<td>Carbachol</td>
<td>25 ± 1</td>
<td>3.1 ± 0.2</td>
<td>9 ± 2</td>
</tr>
<tr>
<td>Atropine</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>45 ± 3</td>
<td>4.5 ± 0.4</td>
<td>10 ± 3</td>
</tr>
<tr>
<td>Atropine</td>
<td>47 ± 5</td>
<td>4.9 ± 0.4</td>
<td>9 ± 2</td>
</tr>
<tr>
<td>Atropine + carbachol</td>
<td>48 ± 4</td>
<td>5.2 ± 0.5</td>
<td>11 ± 3</td>
</tr>
</tbody>
</table>

Results are expressed as mean ± se. Carbachol (carbamylcholine chloride) was infused into the coronary arteries at the rate of 1 μg/kg per min for 6 minutes; n = eight dogs. After a control period, atropine (1 mg/kg) was injected into the femoral vein. Five minutes later, blood samples were drawn and carbachol was infused for 6 minutes; n = six dogs.

Level of significance for changes in concentration of the metabolites at the end of infusion are as follows.

* P < 0.001
† P < 0.01
‡ P < 0.05
§ P < 0.02.
FIGURE 3 A recording from an electrically paced heart of a dog pretreated with atropine (1 mg/kg) followed in 5 minutes by intra-coronary administration of carbachol (1 μg/kg per min).

with no observable change in coronary blood flow or ventricular force. In addition to abolishing these hemodynamic effects, atropine blocked the carbachol-induced changes in uptake of blood substrates (Table 1). Neither atropine alone nor the subsequent infusion of carbachol significantly altered myocardial oxygen extraction ratio or uptake. Atropine treatment alone was found to cause a significant negative extraction of triglycerides, indicating that the heart was releasing the lipid substrate into its venous effluent. These data would suggest that, in addition to preventing changes in coronary blood flow and force of contraction, cholinergic receptor blockade in the heart is capable of influencing triglyceride metabolism.

An experiment representative of the hemodynamic responses recorded in one of the three reserpinized dogs that received a 6-minute infusion of carbachol is shown in Figure 4. Hemodynamic changes associated with the infusion of carbachol were similar to those in Figure 1. However, there was a more pronounced increase in coronary flow in the three pretreated reserpinized dogs in response to carbachol than in the average coronary flow of the first group of dogs (93% vs. 46%). It was apparent that the vasodilating action was more pronounced in the absence of the transmitter norepinephrine in peripheral and coronary blood vessels as shown by the more significant decrease in systemic and coronary perfusion pressure (Fig. 4). In the three reserpinized dogs infused with carbachol, the average myocardial uptake of oxygen slightly decreased from 4.2 to 3.7 ml/min per 100 g, while triglyceride uptake increased from -0.3 to 2.6 mg/min per 100 g and FFA uptake increased from 2.4 to 3.3 μEq/min per 100 g.

Figure 5 shows average changes in dogs on cardiopulmonary bypass in the percent incorporation of radioactive isotopes into myocardial intracellular FFA and triglycerides for five control dogs and six dogs receiving carbachol. At the end of the 6-minute infusion of [14C]-tripalmitin and [3H]-FFA in dogs receiving a simultaneous infusion of carbachol, there was an insignificant increase in the amount of [3H]-FFA that entered the myocardial pool of FFA. In addition, no change was evident in the rate of incorporation of [14C]-tripalmitin into this FFA pool from the breakdown of triglycerides. However, the triglyceride pool into which 9.2 ± 1.1% of [3H]-FFA was incorporated in the control group increased its rate of incorporating [3H]-FFA 3-fold or by 27.6 ± 5.2% (P < 0.02) when carbachol was infused. As a result of the carbachol infusion, triglycerides that were taken up as [14C]-tripalmitin also showed a significant increase in incorporation from a control level of 22.8 ± 4.8% to a level of 57.9 ± 10.4% (P < 0.02).

Discussion

The intracoronary administration of carbachol to dogs subjected to cardiopulmonary bypass indicates that the resulting increase in coronary blood flow cannot be related to changes in coronary perfusion pressure, heart rate, or external cardiac work. The significant increase in coronary flow that was observed could be attributed mainly to stimulation of muscarinic receptors in coronary vessels. Stimulation of receptors in coronary vessels that were classified as muscarinic previously has been reported to result from the administration of ACh by intracoronary route in the open-chest dog. The reported experiments

FIGURE 4 An original recording from one of three dogs on cardiopulmonary bypass showing the effects of carbachol by intracoronary route on systemic and coronary perfusion pressures, right ventricular force, coronary blood flow, and lead II of the electrocardiogram. This group of dogs was chronically depleted of body stores of catecholamines by the administration of reserpine for 2 days prior to the experiment.

FIGURE 5 A comparison of mean changes in percent of radioactivity incorporated by the heart into FFA and triglycerides (TG) in five control dogs and in six dogs treated with carbachol by intracoronary route. Both groups of dogs on cardiopulmonary bypass received [3H]-sodium palmilate and [14C]-tripalmitate simultaneously administered into the coronary circulation. The extension on the bars shows the standard error of the mean.
show that the decrease in ventricular force of contraction caused by carbachol also can be attributed to stimulation of muscarinic receptors, since atropine was found to block this change.

In the absence of external cardiac work, dogs subjected to complete cardiopulmonary bypass were found to have a myocardial oxygen uptake of approximately one-third that of the working heart. The myocardial oxygen uptake of 4.2 ml/min per 100 g agrees with an estimation reported on the oxygen consumption for the beating empty dog heart.\textsuperscript{14} The decrease in force of contraction caused by carbachol was found to be accompanied by a 25\% decrease in oxygen uptake. Both the decrease in force of contraction and oxygen uptake most likely reflect a carbachol-induced depression in utilization of myocardial metabolic substrates. While the metabolic details of cholinergic inhibition in the presence or absence of catecholamines remain to be explained, there are strong indications that the action of cholinergic agents modifies the metabolism of cardiac muscle in a way similar to what has already been reported for ACh. Acetylcholine is known to depress levels of myocardial cyclic AMP\textsuperscript{26} and at the same time elevate cyclic GMP.\textsuperscript{27} In the isolated perfused guinea pig heart, ACh inhibited the stimulating action of epinephrine on glycogenolysis.\textsuperscript{7} Whether increases in cyclic GMP by ACh can be responsible for depression of myocardial metabolism or whether the depression results from the lowered concentration of cyclic AMP remains unexplained. Glaviano et al.\textsuperscript{8} found that, in the dog heart, the intracoronary infusion of ACh in the presence of norepinephrine depressed the enzymic activity of adenylate cyclase and hormone-sensitive lipase. These enzymic changes in cardiac muscle were accompanied by a decrease in the myocardial uptake of oxygen and FFA.

Numerous investigators have found that the isolated perfused heart will show an uptake of triglycerides,\textsuperscript{19} while the extraction of triglycerides by the in situ dog heart has been reported only by Ballard et al.\textsuperscript{19} and Regan et al.\textsuperscript{20} That the heart is capable of extracting plasma triglycerides can be expected from the finding that heart muscle contains a lipoprotein lipase that causes hydrolysis of chylomicron triglycerides.\textsuperscript{21,22} Since arterial levels did not change with the administration of carbachol (Table 2), the increase in myocardial uptake, if a passive mechanism for extracting triglycerides were present, could be attributed in part to the increase in coronary blood flow. However, besides the increase in coronary flow, other factors, such as the level of activity of lipoprotein lipase at the cardiac muscle membrane, may have played a role in the 3-fold increase in triglyceride uptake. Wing and Robinson\textsuperscript{23} showed that epididymal fat bodies studied in vitro and obtained from starved rats have a lowered lipoprotein lipase activity in the presence of Na\textsuperscript{+}-2′-O-dibutyryl-3′,5′-AMP. These investigators further postulated that cyclic AMP, while stimulating the hydrolysis of triglycerides through an intracellular lipase, may inhibit the uptake of triglycerides by depressing lipoprotein lipase, an action not accounted for by the rise in intracellular FFA. More recently, our laboratory showed that ACh by coronary route will slightly lower the activity of adenylate cyclase and will effectively cause a more significant lowering of the enzyme in the presence of norepinephrine.\textsuperscript{24}

The esterification of labeled FFA into triglycerides was accelerated under the influence of carbachol to the extent that the labeled FFA incorporated into triglycerides was increased by more than 3-fold above the level found in the control dog (Fig. 5). These findings indicate that the myocardium probably responds to carbachol by enhancing the lipolysis of triglycerides at the membrane through its action on lipoprotein lipase while simultaneously causing the inhibition of triglyceride degradation by depressing levels of cyclic AMP. The hypothesis that cyclic AMP may have a dual action on lipid enzymes of cardiac muscle could be supported by previously reported studies on the intracoronary administration of prostaglandin E\textsubscript{1}. Administration of prostaglandin E\textsubscript{1} to open-chest dogs caused an increase in cardiac muscle concentration of triglycerides while simultaneously depressing intracellular hormone-sensitive lipase.\textsuperscript{25} The inverse relationship between intracellular accumulation of triglycerides and the decline in intracellular lipase was attributed to the decrease found in myocardial levels of cyclic AMP. Similar to the findings with prostaglandin E\textsubscript{1}, carbachol inhibited triglyceride hydrolysis. This inhibitory action of carbachol can be substantiated by the 200\% increase of [\textsuperscript{14}C]-triglyceride incorporated into cardiac muscle (Fig. 5).

The administration of carbachol to the reserpinized dog on cardiopulmonary bypass resulted in a more significant decrease in systemic and coronary perfusion pressures and a 2-fold increase in coronary blood flow (Fig. 4). The decrease in right ventricular force of contraction was approximately equal to that observed in the nonreserpinized dog receiving carbachol. The enhancement of coronary flow by carbachol in the catecholamine-depleted heart would indicate that maximal coronary vasodilation cannot be achieved by cholinergic stimulation alone unless the vasoconstrictor influence of underlying sympathetic activity on the coronary vessels is blocked. These experiments on the reserpinized dog would also eliminate a possible action of carbachol on increasing the uptake of triglycerides by stimulating the release of norepinephrine.\textsuperscript{25,26}

These data suggest that the utilization of metabolic substrates by the heart could be controlled in part by its autonomic nervous secretion of norepinephrine and ACh. While these neurohormones in the laboratory animal have been shown in the past to alter cardiac muscle dynamics, both also could be regarded as having the additional action of affecting the uptake and subsequent utilization of metabolic substrates extracted by the heart. It is generally accepted that norepinephrine will elevate levels of cyclic AMP, which as a second messenger to the neurohormone will in turn regulate glycogen phosphorylase activity and hydrolysis of triglycerides by intracellular lipases. These reactions to sympathetic nervous system stimulation can be countered by the neurohormone ACh, whose inhibitory actions are far more pronounced if a sympathetic background is present.\textsuperscript{28} Thus, the metabolic events that have been accelerated by one component of the autonomic nervous system can be effectively antagonized by its counterpart, an interaction seen when physical or metabolic
parameters are measured in the in situ heart. The implications that can be drawn from an altered state of neurohumoral control of cardiac metabolism would be that an imbalance in the heart favoring the parasympathetic components of the autonomic nervous system can lead to accumulation of myocardial triglycerides.

References

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