Effects of Calcium and Its Antagonists on the Canine Mesenteric Circulation

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SUMMARY We studied circulatory and metabolic responses of the intestinal circulation to intravascular infusions of solutions containing calcium chloride or calcium antagonists in anesthetized dogs. Measurements included blood flow to the terminal ileum, arteriovenous oxygen content difference, distribution of radiolabeled microspheres to the mucosal-submucosal compartment and intraluminal pressure. Calculated parameters included oxygen consumption and fractional mucosal-submucosal blood flow. Both calcium antagonists, nifedipine and diltiazem, increased intestinal blood flow, mainly by increasing the concentration of free Ca$^{2+}$ in the cytoplasm, thereby activating contractile proteins (Somlyo and Somlyo, 1970; Johansson, 1978; Winquist and Bevan, 1980). There are two main sources of activator Ca$^{2+}$, namely, the pool of extracellular Ca$^{2+}$, as well as with the slow inward current of calcium.
shown to influence the two sources of Ca\(^{2+}\) differently. For instance, contraction induced by depolarizing concentrations of potassium is the result of an augmented flux of Ca\(^{2+}\) from the extracellular space, whereas the vasoconstriction induced by norepinephrine involves primarily the release of intracellular Ca\(^{2+}\) (Hudgins and Weiss, 1968; Seidel and Bohr, 1971; Godfraind and Kaba, 1972; Bohr, 1978).

Effects of Ca\(^{2+}\) on the intestinal circulation have not been studied extensively and vascular responses appear minimal (Chou et al., 1963; Dabney et al., 1967; Pawlik et al., 1975). Furthermore, calcium ionophores are minimally active (Hanley et al., 1975; Lanciult et al., 1976). Recently, a group of chemically different compounds was introduced which are believed to exert a negative inotropic effect and relax vascular smooth muscle by a selective inhibition of membrane Ca\(^{2+}\) flux, i.e., by reducing the slow inward current (Fleckenstein, 1977; Fleckenstein and Fleckenstein-Grün, 1977).

Effects of calcium antagonists in the intestinal circulation have received little attention (Schwaiger et al., 1977; Fleckenstein and Fleckenstein-Griin, 1977). Since such pathological changes also occur in the mesenteric vasculature (Marston, 1977; Bynum and Jacobson, 1979) a search among the calcium antagonists for a potentially useful agent for the management of intestinal ischemia would appear justified.

The aim of our present study was to investigate the effects of calcium and two calcium antagonists, nifedipine and diltiazem, on the intestinal circulation, its oxygen consumption, and the distribution of intestinal blood flow in vivo. Attempts also were made to elucidate the mechanism of action of nifedipine on mesenteric arterial smooth muscle in vitro.

**Methods**

A total of 29 mongrel dogs of both sexes, weighing between 16 and 28 kg (average 20.6 kg) were used in this study. Of these animals, 25 were studied under in vivo conditions, and four dogs were used to obtain mesenteric arteries for in vitro experiments. All animals were deprived of food for 24 hours and anesthetized with intravenous (iv) injection of sodium pentobarbital (30 mg/kg).

**In Vivo Experiments**

After endotracheal intubation, ventilation was maintained with a positive pressure respirator (Harvard Apparatus) at a rate adjusted to body weight. A femoral artery was cannulated and connected to a pressure transducer (Hewlett-Packard) for recording the arterial pressure and for siphoning arterial blood into one cuvette of a spectrophotomet-
ion Laboratories) (both agents infused at 0.1, 1.0, and 10.0 μg/kg per min), or calcium chloride (CaCl₂ at 1.0, 10.0, 100.0, 500.0, and 1,000.0 μg/kg per min) were obtained.

Extreme care was taken to minimize the exposure of nifedipine to light. This was accomplished by weighing the drug in a dark room on a balance having an illuminated dial and dissolving the agent in a solution (ethanol 15%, polyethylene glycol 15% in saline) contained in a flask covered with aluminum foil in a room with faint indirect light. The infusion pump syringe containing dissolved nifedipine and the polyethylene tube conveying the drug to the mesenteric artery were wrapped in aluminum foil. The pump, syringe, tubing, and dog were covered with surgical towels throughout the experiment. In another series of experiments, the effects of nifedipine (0.1 μg/kg per min) on responses to CaCl₂ (500.0 μg/kg per min) or norepinephrine (0.1 μg/kg per min) were investigated by infusing each of the constrictors with nifedipine. The duration of infusion with each agent was 10 minutes.

In an additional series of experiments, an attempt was made to explore the unexpected vasodilator effect of the highest dose of CaCl₂. First, the effects of i.a infusions of comparably hyperosmotic (1100 mOsm) solutions of NaCl (3.6%) or mannitol (20%) were assessed. Second, the dilator dose of CaCl₂ was infused after iv administration of digoxin (Lanoxin, Burroughs-Wellcome Co., 50 μg/kg).

In Vitro Experiments

Four additional dogs were used to obtain muscle strips from the superior mesenteric artery. Following anesthesia and laparotomy the vessel was quickly excised, carefully cleaned of surrounding tissues, and opened longitudinally. Strips of circular muscle 10 to 12 mm long and 2 mm wide were then cut. Four strips were mounted in a single muscle chamber with one end of each strip fixed to the glass post and the other end connected with silk thread to a Grass FT 0.03 transducer. Strips were stretched passively to optimal length were covered with surgical towels throughout the experiment. The pump, syringe, tubing, and dog were wrapped in aluminum foil. The pump, syringe, tubing, and dog were covered with surgical towels throughout the experiment. In another series of experiments, the effects of nifedipine (0.1 μg/kg per min) on responses to CaCl₂ (500.0 μg/kg per min) or norepinephrine (0.1 μg/kg per min) were investigated by infusing each of the constrictors with nifedipine. The duration of infusion with each agent was 10 minutes.

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In Vivo Studies

Control values for 25 dogs were: BF 65.6 ± 4.7 ml/min per 100 g of intestinal tissue, A-VO₂ 3.1 ± 0.3 ml O₂/ml of blood, VO₂ 2.0 ± 0.2 ml O₂/min per 100 g of intestine, the fraction of total blood flow which perfused the muscularis 30.6 ± 3.5%, FBF 45.0 ± 3.4 ml/min per 100 g of intestine, and IP 4.8 ± 0.7 mm Hg. Systemic arterial pressure was not changed significantly during any series of tests. The weight of intestinal segments averaged 208.5 g.

Infusion of the three doses of nifedipine produced a dose-dependent increase in BF and decreases in A-VO₂, VO₂, and FBF. The calculated dose of the drug producing a 50% increase in BF was 0.36 μg/kg per min or 1 × 10⁻⁹ mol/kg per min (Fig. 1). Diltiazem evoked similar responses, but was less potent. The calculated dose of diltiazem causing a 50% increase in BF was 3.3 μg/kg per min or 7.3 × 10⁻⁹ mol/kg per min (Fig. 2). After cessation of

Results

In Vivo Studies

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Infusion of the three doses of nifedipine produced a dose-dependent increase in BF and decreases in A-VO₂ and IP. The two higher doses of nifedipine also caused increases in m-s and FBF. The calculated dose of the drug producing a 50% increase in BF was 0.36 μg/kg per min or 1 × 10⁻⁹ mol/kg per min (Fig. 1). Diltiazem evoked similar responses, but was less potent. The calculated dose of diltiazem causing a 50% increase in BF was 3.3 μg/kg per min or 7.3 × 10⁻⁹ mol/kg per min (Fig. 2). After cessation of
infusion of either agent, all measured parameters returned to control within a few minutes.

CaCl₂ produced a dose-dependent decrease in BF up to a dose of 500.0 μg/kg per min. At a dose of 1,000.0 μg/kg per min, CaCl₂ caused a significant increase in BF. A-V<sub>o₂</sub> was increased at all doses of CaCl₂, although at lowest and highest doses the changes were not significant. V<sub>o₂</sub> changed significantly only at the 1,000.0 μg/kg per min dose, when it increased (Fig. 3). IP increased in a dose-dependent manner with the 100.0, 500.0, and 1,000.0 μg/kg per min doses of CaCl₂. The intestinal contractions were of both rhythmic and tonic type and were observed mainly at the beginning of infusion of each dose. Since the distribution of microspheres was not changed significantly at any dose, changes in FBF<sub>m-s</sub> paralleled those of BF. These data were omitted for the sake of clarity.

The lowest dose of nifedipine, infused together with the highest constrictor dose of CaCl₂, completely blocked the effects of CaCl₂. Thus, the effects of nifedipine + CaCl₂ were not significantly different from those of nifedipine alone (Fig. 4). Nifedipine also partially inhibited the vasoconstrictor response to norepinephrine. Control infusion of the catecholamine decreased BF, V<sub>o₂</sub>, m-s and FBF<sub>m-s</sub> and increased A-V<sub>o₂</sub>. Norepinephrine infused with nifedipine produced significantly smaller changes in all parameters except V<sub>o₂</sub> than did norepinephrine alone (Fig. 5).

Digoxin reduced BF and V<sub>o₂</sub> and increased A-V<sub>o₂</sub> (Fig. 6). CaCl₂ (1,000.0 μg/kg per min) infused 10-15 minutes after injection of digoxin exerted a small vasoconstrictor effect; thus, BF decreased and A-V<sub>o₂</sub> increased, whereas V<sub>o₂</sub> decreased when compared with control values before digoxin. BF and A-V<sub>o₂</sub> were significantly different from values observed with digoxin alone.

In Vitro Experiments

KCl (30 mM) and norepinephrine (0.1 μM) were equipotent in contracting strips of mesenteric artery in normal PSS, i.e., contractile tensions obtained with both agonists were not significantly different. As shown in Figure 7 in normal PSS, mean control
Effects of CaCl₂ on BF, A-V̇O₂, and V̇O₂. Numbers in brackets indicate numbers of determinations at a particular dose. Other symbols as in Figure 1.

The tension obtained with KCl was 8.2 ± 0.8 g and that obtained with norepinephrine was 9.6 ± 1.1 g in the same strips. In calcium-free PSS, control tension obtained with KCl was reduced to 1.5 ± 0.2 g and in the same strips norepinephrine induced a tension of 7.4 ± 1.2 g. These values were significantly different (P < 0.001). In calcium-free PSS with EGTA, KCl-contracted strips developed a tension of 0.7 ± 0.1 g, whereas norepinephrine-induced contractions of the same series of strips averaged 5.0 ± 1.1 g. These values again were significantly different (P is less than 0.005).

Additional control tests involved repetitive challenges with either agonist in normal PSS and Ca²⁺-free PSS with EGTA. Contractile responses to consecutive challenges with KCl were not different from one another and were very well sustained so long as the excess of KCl was not washed out. Responses to consecutive challenges with norepinephrine in normal PSS were also not different from one another and were well sustained; however, in Ca²⁺-free PSS and Ca²⁺-free PSS with EGTA, contractile responses to norepinephrine reached their maxima within 1-2 minutes and then decreased at a steady rate. Therefore, in experiments in which norepinephrine was used as the contractile agonist, before assessing the effects of nifedipine, the rate of spontaneous decrease in tension was established for each strip over a period of 30-35 minutes, and decreases in tension obtained with increasing concentrations of nifedipine then were significantly different (P < 0.001).
Figure 6  Comparison of the effects of CaCl₂ (dilator dose) before and after digoxin. + indicates significant difference between digoxin alone and digoxin + CaCl₂. Other symbols as in Figure 1.

corrected for the spontaneous decrease in tension during the control test for each corresponding period of time.

Nifedipine administered in concentrations increasing from 10⁻⁹ to 10⁻⁷ M every 5 minutes pro-
duced a concentration-dependent relaxation of KCl-contracted strips in normal PSS and of strips con-
tracted with norepinephrine in normal PSS (Fig. 8). The ED₅₀ (dose producing 50% relaxation) under these conditions was 7.1 × 10⁻⁷ M in KCl contracted strips and 3.3 × 10⁻⁸ M in norepinephrine-con-
tracted strips. The same concentrations of nifedi-
pine relaxed strips contracted by norepinephrine in Ca²⁺-free PSS and in Ca²⁺-free PSS with EGTA. After assessing the dose-response to nifedipine, the strips were washed several times and challenged again after 20 minutes. All responses were signifi-
cantly depressed (Fig. 7, hatched bars) up to 3 hours after the experiments were terminated.

Discussion

The results of our in vivo studies indicate that both nifedipine and diltiazem are potent dilators of the intestinal circulation. Comparison of doses producing a 50% increase in blood flow to the ileum shows that nifedipine is about 7 times more potent than diltiazem on a molar basis. It appears that both agents dilate arteriolar resistance vessels in the intestinal circulation, while decreasing the tone
of large arteries as an additional effect. The latter effect has been suggested in the coronary circulation (Fleckenstein and Fleckenstein-Grün, 1977) but cannot alone account for such large increases in blood flow to the gut as were observed with these drugs. Vasodilation occurred mainly in the mucosa-submucosa with the calcium antagonists indicating that these compounds produce a redistribution of intestinal blood flow to the mucosal-submucosal compartment. This redistribution may have been related to the decrease in intestinal motor activity observed with these drugs, reflecting the important role of calcium in mediating contractile activity of both vascular and visceral smooth muscle (Anderson et al., 1972).

Dose-related increases in blood flow observed with the calcium antagonists were accompanied by proportional decreases in oxygen extraction across the intestinal circulation and resulted in no change in oxygen consumption by the gut. The lack of change in oxygen uptake suggests that the main micro-circulatory effect of these compounds, relaxation of arterioles, was not accompanied by any apparent relaxation of precapillary sphincters which regulate the nutrient circulation. The increased blood flow which bypasses the nutrient circulation thereby represents a functional arteriovenous shunting. It is also possible that Ca2+ antagonists depress intestinal function(s) and, therefore, reduce oxygen use by the gut, as has been shown in the myocardium (Fleckenstein, 1977; Fleckenstein and Fleckenstein-Grün, 1977). Were this the case, the decrease in oxygen utilization would nullify any effect of opening the precapillary sphincters. The more likely of these two explanations cannot be ascertained from our data.

Previous studies of the interactions of calcium antagonists with cardiac glycosides in the coronary and intestinal circulations showed that the antagonists appear to have different effects in the normal and digitalis-poisoned circulations.

In contrast to the high potency of calcium antagonists in the intestinal circulation, Ca2+ itself evoked very small constrictor effects in this vascular bed. Chou et al. (1963) reported a 10% increase in total intestinal resistance and a 20% increase in small-vessel resistance in response to an isotonic CaCl2 infusion at a rate of about 8 ml/min. The same group reported later that Ca2+ relaxed visceral smooth muscles but had no significant effect on intestinal resistance (Dabney et al., 1967). Infusion of CaCl2 at 300 μg/kg per min into the mesenteric artery was reported to decrease both blood flow and oxygen consumption by 12% (Pawlik et al., 1975). Maximal constriction obtained with CaCl2 in the present study corresponded to about a 20% decrease in blood flow. The dose-dependent decrease in blood flow was accompanied by an increase in oxygen extraction and no change in oxygen uptake, typical of a weak vasoconstrictor effect in this circulation. The highest dose of CaCl2 (1,000 μg/kg per min) produced, unexpectedly, a reproducible intestinal vasodilation accompanied by an increase in oxygen consumption. In additional experiments not reported here still higher doses of CaCl2 (2,000.0 and 5,000.0 μg/kg per min) prompted progressively greater dilator responses. We thought this vasodilation might be a function of the hyperosmolality of the CaCl2 solution infused into the artery, since administration of hyperosmolar glucose or NaCl was shown to decrease vascular resistance in the feline intestinal circulation (Levine et al., 1978). In our study, however, solutions of NaCl or mannitol of the same osmolarity as the 1,000.0 μg/kg per min solution of CaCl2 infused i.a. did not change any circulatory or metabolic parameter. The vasodilator effect of the 1,000.0 μg/kg per min dose of calcium may be related to its effect on the membrane-bound Na+, K+-ATPase of the muscle cell. This enzyme is blocked by cardiac glycosides (Akerl, 1977), and this effect probably accounts for the vasoconstrictor effect of digitalis in the intestinal circulation (Pawlak and Jacobson, 1974; Schweiger et al., 1979). After blockade of Na+, K+-ATPase by digoxin, the dilator effect of the highest dose of CaCl2 was converted to a constrictor effect.

None of the doses of CaCl2 changed the distribution of intestinal blood flow, suggesting that vasocostriction or vasodilation was proportional in all intestinal layers. The three higher doses of CaCl2 also stimulated intestinal motility, a finding which is not in agreement with reports of others wherein a decrease in tone of intestinal musculature was observed with Ca2+ (Dabney et al., 1967). The stimulation of intestinal motility by Ca2+ is, however, consistent with the inhibitory effects on motility we observed with calcium antagonists and suggests that qualitative similarities exist between the role of Ca2+ in contractility of vascular and nonvascular smooth muscle. The suggestion that effects of ions on visceral smooth muscle may interfere with their action on vascular resistance (Chou et al., 1963; Dabney et al., 1967) appears unlikely, since a dose-related increase in intraluminal pressure was found with the three highest doses of CaCl2, whereas intestinal blood flow was first diminished and then augmented (at highest dose when the amplitude of intestinal contractions was highest). Our observations suggest different sensitivities of vascular and visceral smooth muscle to the increments of plasma Ca2+ concentrations.

Ca2+ may act through several mechanisms in vascular smooth muscles. First, a rise in extracellular Ca2+ increases the transmembrane concentration gradient, the membrane Ca2+ influx, and the intracellular concentration of the ion. This effect is not very pronounced, probably because much of the Ca2+ entering the cell is easily sequestered in intracellular stores before it can activate contractile proteins. Second, Ca2+ may stabilize the cell membrane or may stimulate Na+, K+-ATPase. Inhibition of vascular tone in vitro by supranormal extracel-
lular concentrations of Ca²⁺ has been shown previously (Winquist and Bevan, 1980). Whether this effect occurs over the entire range of concentrations and thus minimizes the direct constrictor effect or occurs only at very high concentrations remains to be established in studies of the direct effects of calcium on isolated enzymes.

Nifedipine completely blocked the circulatory effects of the highest constrictor dose of calcium but only partially reduced the constrictor response of the intestinal circulation to norepinephrine. It is possible that reduction of norepinephrine-induced constriction reflects the ability of nifedipine to block increased Ca²⁺ influx which accounts in part for the constrictor action of the drug (Seidel and Bohr, 1971; Godfraind and Kaba, 1972; Bohr, 1978; Johannson, 1978; Meisheiri et al., 1980). Nifedipine is commonly believed to interfere with the slow inward current, i.e., transmembrane Ca²⁺ influx, or to reduce the number of slow channels (Fleckenstein, 1977; Fleckenstein and Fleckenstein-Grün, 1977; Bayer and Ehara, 1978; but an effect on intracellular calcium release has also been proposed (Church and Zsoter, 1980). Under in vitro conditions, nifedipine appeared to be a very effective relaxant of mesenteric arterial strips contracted with either norepinephrine or KCl and produced almost complete relaxation whether or not extracellular calcium was present in the medium. It is well established that KCl-induced contraction uses extracellular calcium whereas norepinephrine-mediated contraction depends on both extra- and intracellular Ca²⁺ (Hudgins and Weiss, 1968; Seidel and Bohr, 1971; Godfraind and Kaba, 1972; Bohr, 1978; Meisheiri et al., 1980) van Breeman et al., 1979). The ED₅₀ of nifedipine fed norepinephrine-contracted strips was more than one order of magnitude lower than for KCl-contracted strips. This difference may mean that nifedipine relaxes vascular smooth muscle both by blocking Ca²⁺ influx and by preventing Ca²⁺ release from intracellular stores.

To exclude Ca²⁺ influx, we performed studies on the norepinephrine-nifedipine interaction after removing Ca²⁺ from the extracellular medium. In both Ca²⁺-free PSS and Ca²⁺-free PSS with EGTA, norepinephrine still produced constriction, in contrast to KCl. This differential effect of Ca²⁺ removal on vascular smooth muscle from rat aorta was demonstrated previously by Hudgins and Weiss (1968), and our results confirm their findings. Contractions obtained with norepinephrine after removal of Ca²⁺ were not sustained. This finding is consistent with the suggestion that the tonic response to norepinephrine is due to increased uptake of external Ca²⁺ in contrast to the phasic (initial) response which depends upon release of Ca²⁺ from internal stores (Godfraind and Kaba, 1972). The difference probably is not discrete because phasic responses to norepinephrine in normal, Ca²⁺-free and Ca²⁺-free PSS with EGTA differ significantly. On the other hand, a part of the tonic response may also depend on intracellular Ca²⁺ release since the decrease in tension after norepinephrine was relatively slow in the absence of Ca²⁺. Addition of nifedipine in increasing concentrations accelerated the spontaneous decay of tension.

Nifedipine irreversibly blocked any subsequent responses to KCl or norepinephrine in any type of PSS. Thus, the drug interferes not only with KCl-induced contraction and the tonic response to norepinephrine, both of which depend mainly on extracellular Ca²⁺, but also with the phasic response to the catecholamine. In the absence of external Ca²⁺ (as is the case in Ca²⁺-free PSS with EGTA), the phasic response depends entirely on intracellular Ca²⁺. It appears that Ca²⁺ antagonism by nifedipine involves blockage of both Ca²⁺ influx and Ca²⁺ release from intracellular sites. Increased Ca²⁺ influx is also possible as a mechanism of nifedipine-induced relaxation (Fleckenstein and Fleckenstein-Grün, 1977). Our results generally confirm the results of studies of Ca²⁺ fluxes under the influence of calcium antagonists (Church and Zsoter, 1980). The quantitative contribution of the preceding mechanisms to the vasodilator effects of these compounds cannot be established at this point.

In Ca²⁺-free media, maximum relaxation of norepinephrine-contracted strips is much less than that of norepinephrine or KCl-contracted strips in the presence of Ca²⁺. Furthermore, at low concentrations of nifedipine, relaxation of strips contracted with norepinephrine in all types of PSS is similar to relaxation of strips contracted with KCl. These findings support the speculation that Ca²⁺ antagonists in low doses interact in a major way with the intracellular free Ca²⁺ pool. When the concentration of the drug is high, these drugs also affect membrane calcium flux, and produce additional relaxation. It is possible that studies of calcium fluxes in vascular smooth muscle might bear upon these speculations, although recent experiments (Church and Zsoter, 1980) using such techniques did not appear to yield definitive results.

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