

Pharmacological characterization of the ergot alkaloid receptor in the salivary gland of the ixodid tick *Amblyomma hebraeum*

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Summary

Female ticks of the family Ixodidae osmoregulate by secreting the excess fluid of the blood meal back into the host's circulation *via* the salivary glands. At least three receptors control salivary fluid secretion in the tick *Amblyomma hebraeum*: (1) dopamine (DA) stimulates fluid secretion *via* a DA receptor, (2) ergot alkaloids (ErAs) stimulate fluid secretion *via* an ErA-sensitive receptor (the natural ligand of which has not been identified), and (3) a GABA receptor potentiates the action of DA and ErAs. Here we present some pharmacological properties of the ErA-sensitive receptor. Of the 11 ErAs we tested, (i) four were complete agonists (approximate concentration eliciting 50% maximum response is given in parentheses): dihydroergotamine (0.02 $\mu\text{mol l}^{-1}$), ergonovine (ErN; 0.06 $\mu\text{mol l}^{-1}$), methylergonovine (0.1 $\mu\text{mol l}^{-1}$) and α -ergocriptine (0.9 $\mu\text{mol l}^{-1}$); (ii) three were 'incomplete agonists' (approximate concentration eliciting 20% maximum response is given in parentheses): ergocorninine (3.5 $\mu\text{mol l}^{-1}$), ergocristinine (7.5 $\mu\text{mol l}^{-1}$) and ergocristine (10 $\mu\text{mol l}^{-1}$); (C) three were partial agonists (approximate concentration eliciting the respective maximum response in parentheses): ergocornine (50% maximum by 1 $\mu\text{mol l}^{-1}$), methysergide (28% maximum

by 10 $\mu\text{mol l}^{-1}$) and bromocriptine (22% maximum by 10 $\mu\text{mol l}^{-1}$); and (D) one had no activity up to 1 mmol l^{-1} : ergothioneine. Bromocriptine and methysergide did not antagonize the action of DA, but were effective competitive antagonists of ErN, with K_{is} of $\sim 0.3 \mu\text{mol l}^{-1}$ and 11 $\mu\text{mol l}^{-1}$, respectively. Ergothioneine was not an antagonist of either the DA- or ErA-sensitive receptor. The putative protein kinase C activators, 1-oleoyl-2-acetyl-sn-glycerol (OAG) and 1,2-dioctanoyl-sn-glycerol (DiC₈), neither stimulated salivary fluid secretion nor potentiated the action of DA or ErN. The putative protein kinase C inhibitors, bisindolymaleimide (BIM) and calphostin C did not inhibit the action of DA or ErN, although low concentrations of calphostin C (10 nmol l^{-1}) appeared to potentiate the action of DA but not ErN. The ion transport inhibitors, furosemide and amiloride (both up to 1 mmol l^{-1}), had no significant effect on DA-stimulated or ErN-stimulated fluid secretion.

Key words: *Amblyomma hebraeum*, bromocriptine, dihydroergotamine, ergocornine, ergocorninine, ergocristine, ergocristinine, ergocryptine, ergonovine, ergothioneine, ergot alkaloids, methylergonovine, methysergide, tick salivary gland.

Introduction

Female ixodid ticks feed on a host for 7–14 days, during which time they concentrate the nutrient part of the blood meal by secreting a large volume of hyposmotic saliva. The total saliva secreted over the complete feeding period equals or exceeds the final engorged weight of the tick (reviewed by Kaufman, 1989; Sauer et al., 2000; Bowman and Sauer, 2004). Control of fluid secretion is mediated *via* at least three receptors. Dopamine (DA) and other catecholamines stimulate secretion *via* a DA receptor. This receptor appears to be in the D-1 family (Schmidt et al., 1981; Schmidt et al., 1982). γ -Aminobutyric acid (GABA) potentiates the fluid secretion stimulated by DA *via* a distinct receptor, but GABA has no intrinsic activity (Lindsay and Kaufman, 1986). The fact that muscimol, but not baclofen, mimics the potentiation of GABA,

suggests that this receptor is of the GABA_A type. The effect of GABA is blocked by picrotoxin (100 $\mu\text{mol l}^{-1}$) and (-)-bicuculline (100 $\mu\text{mol l}^{-1}$) in a non-competitive manner (Lindsay and Kaufman, 1986).

The ergot alkaloid (ErA), ergonovine (ErN), is also a very potent agonist of salivary fluid secretion (Kaufman and Wong, 1983). Results with selective antagonists demonstrate that ErN acts *via* a receptor distinct from the DA receptor (Kaufman and Wong, 1983). We call this third receptor an 'ErA-sensitive receptor' because we do not know the identity of its natural ligand.

Similar to other D-1 receptors, the effect of DA on this tissue is mediated by cAMP (Schmidt et al., 1981; Schmidt et al., 1982). Supramaximal concentrations of ErN also stimulate adenylate cyclase activity in the tick salivary glands, but only

to ~50% of the level stimulated by supramaximal concentrations of DA (W.R.K., unpublished observations), suggesting that the intracellular pathway mediating the action of ErN may be somewhat different from that of DA.

ErAs elicit an enormously broad spectrum of pharmacological effects, the best known being at adrenergic, dopaminergic and tryptaminergic receptors (Berde and Schild, 1978; Peroutka, 1996; Pertz and Eich, 1999), probably because the structures of these biogenic amines can be exactly superimposed onto specific parts of the ergoline ring structure (Berde, 1980). The purpose of this study was to extend our characterization of the pharmacological properties of the ErA-sensitive receptor in the tick salivary gland. We constructed dose–response curves for 11 ErAs available to us. Non-agonists and partial agonists were tested as putative inhibitors of the ErA and DA receptors. We also tested some inhibitors and activators of protein kinase C (PKC) for differential effects on the DA and ErN pathways. Likewise, we tested two inhibitors of ion transport (amiloride and furosemide) for differential effects on the two pathways.

Materials and methods

Ticks

All animal use in the Department of Biological Sciences, University of Alberta, is reviewed by the Biosciences Animal Policy and Welfare Committee according to the Guidelines established by the Canadian Council on Animal Care. *Amblyomma hebraeum* (Koch) were taken from a laboratory colony raised in darkness, at 26°C and high relative humidity. Ticks were fed on rabbits as originally described for *Dermacentor andersoni* by Kaufman and Phillips (Kaufman and Phillips, 1973a). For this study we used partially fed ticks in the range of 80–300 mg (normal engorged mass of *A. hebraeum* is in the range of 1000–3000 mg).

Drugs and media

Modified Hank's saline (dissection medium)

Composition in g l⁻¹ was: 11.5 NaCl, 1.6 D-glucose, 0.4 KCl, 0.14 CaCl₂, 0.098 MgSO₄, 0.06 KH₂PO₄, 0.05 NaHPO₄, 0.01 Phenol Red. The pH was adjusted with NaOH to 7.2; the osmotic pressure was ~360 mOsm.

Modified TC 199 (in-vitro bathing medium)

1 package powdered TC199 (11 g; Gibco, Town, State, Country), 2.1 g NaCl and 2.09 g 3-[N-morpholino]propanesulfonic acid (Mops; Sigma Chemical Co., St Louis, MO, USA) were dissolved in distilled-deionized water, the pH was adjusted with NaOH to 7.2 and the final volume was brought to 1 l.

The following drugs were a gift from Hoffman LaRoche (Basle, Switzerland): bromocryptine, methylergonovine, ergocristine, ergocristinine, ergocornine, ergocorninine and methysergide. (+/-)-Sulpiride (Ravizza, Italy or Delagrang, France) was a gift from Dr G. N. Woodruff, formerly of the

University of Southampton, UK. The following drugs were purchased from Sigma: DA-HCl, ergonovine-maleate, dihydroergotamine, α-ergocryptine, ergothioneine and 5-hydroxytryptamine (5-HT). Structures of the ErAs used in this study [plus ergotamine from Kaufman (Kaufman, 1977)] are shown in Fig. 1. Deprenyl [monoamine oxidase (MAO) inhibitor] was purchased from Research Biochemicals Inc. (Natick, MA, USA). 1-oleoyl-2-acetyl-sn-glycerol (OAG), 1,2-dioctanoyl-sn-glycerol (DiC₈), bisindolymaleimide (BIM) and calphostin C, were purchased from Calbiochem (San Diego, CA, USA).

Stock solutions of all drugs were made daily; DA, deprenyl, ErN, methylergonovine, ergothioneine and methysergide were each dissolved in double-deionized water (to 1 or 10 mmol l⁻¹) and then diluted to working concentration in modified TC 199. Calphostin C, OAG, DiC₈, BIM, ergocryptine, bromocryptine, dihydroergotamine, ergocornine, ergocorninine, ergocristine, ergocristinine were each dissolved in dimethylsulphoxide (DMSO; 0.5 mmol l⁻¹, 1 mmol l⁻¹, 2 mmol l⁻¹ or 10 mmol l⁻¹) and then diluted to working concentration in modified TC 199 such that the final concentration of DMSO did not exceed 1%; we have demonstrated previously that this concentration of DMSO does not significantly affect the rate of salivary fluid secretion *in vitro* (Lindsay and Kaufman, 1986).

In vitro technique for measuring salivary fluid secretion

The technique was similar to that described by Kaufman and Phillips (Kaufman and Phillips, 1973b) and Wong and Kaufman (Wong and Kaufman, 1981). Glass Petri dishes (15 cm diameter) were lined with paraffin wax into which four fine glass posts were embedded to serve as anchors for the experimental glands. The Petri dishes were filled with liquid paraffin (light mineral oil; Fisher Scientific, Town, State, Country). Briefly, salivary glands were dissected out under modified Hank's saline with their main ducts completely intact. The glands were transferred to modified TC 199 and extraneous tissue clinging to the main duct was teased away. Fine silk thread was ligated to a fragment of cuticle associated with the terminal portion of the main duct, but without occluding the orifice. The glands were then transferred to the Petri dish in a droplet of bathing medium such that the bathing medium adhered to the glass post and the silk thread draped over the far rim of the Petri dish. The thread was then gently pulled so that the main duct protruded from the bathing droplet into the mineral oil. Whenever the bathing medium contained an effective agonist, a small, spherical droplet of secreted fluid would appear and grow at the orifice of the main duct. For measuring the amount of secreted fluid, the droplet was removed from the orifice with a fine glass rod, allowed to sink, the diameter measured under a stereomicroscope fitted with an ocular micrometer, and the sphere volume calculated from the diameter of the droplet.

General experimental protocol

All experiments were done at room temperature (22.5±0.5°C). Glands were exposed to a control treatment

(usually a given concentration of agonist), and the rate of secretion was recorded every 3–5 min until an equilibrated rate for that treatment was observed (usually 10–20 min). During this time, the prevailing medium was changed for a fresh droplet every 3–5 min. Then the glands were exposed to successively higher concentrations of drug, each time an equilibrated rate of secretion being recorded following similar

changes of prevailing medium. Concentration of drug was increased by 10-fold increments until the response was maximal. When the drug under consideration was not DA, the glands were then washed in drug-free TC 199 for at least 20 min, and then exposed to 10 $\mu\text{mol l}^{-1}$ DA for three to five 3-min readings. Unless otherwise stated, the response of the glands to 10 $\mu\text{mol l}^{-1}$ DA was designated as 100%, and the

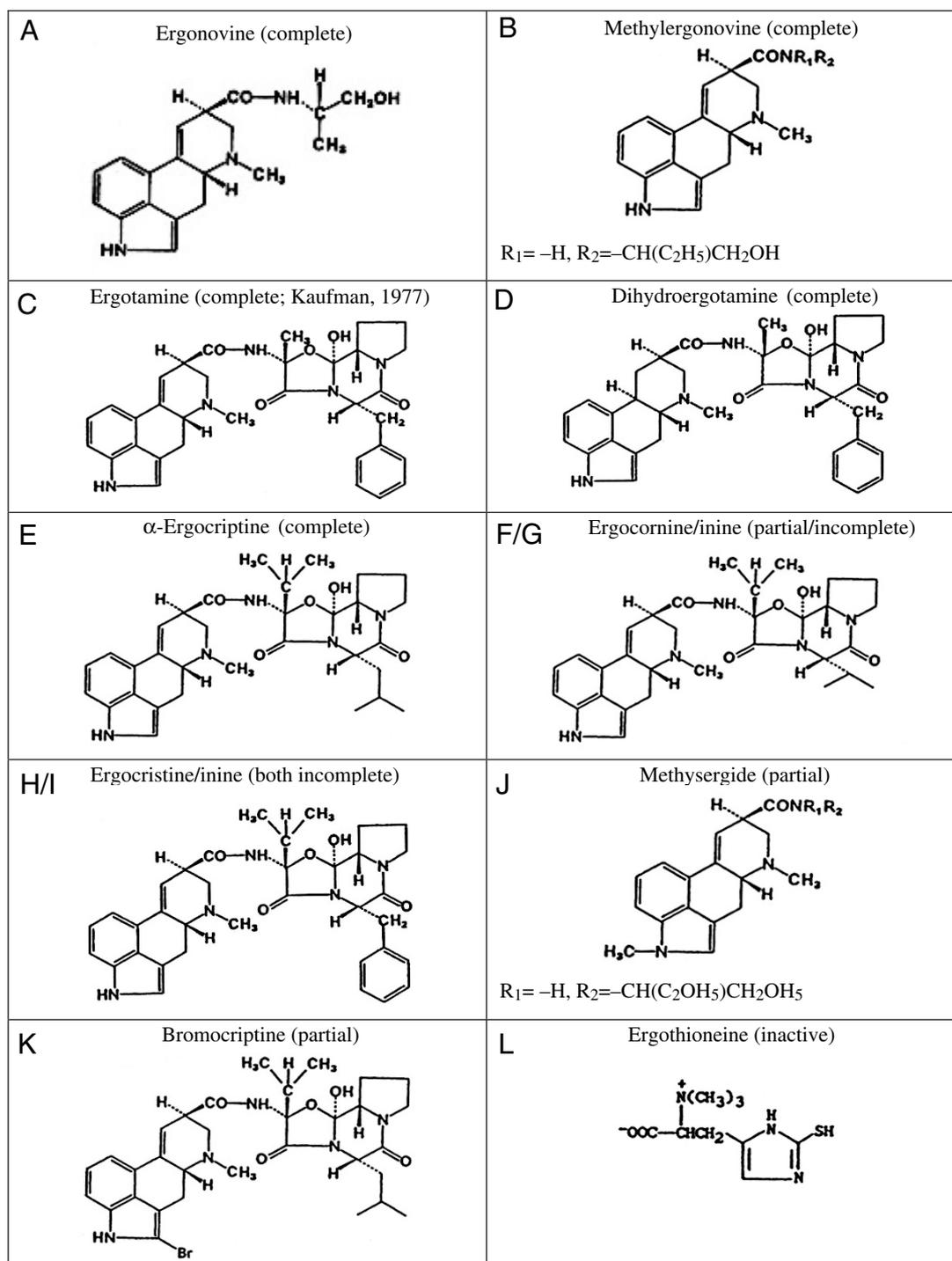


Fig. 1. (A–L) Ergot alkaloids tested on tick salivary glands. The agonist activity for each is indicated in parentheses. All structures compiled from (Berde and Schild, 1978). Reproduced with kind permission of Springer Science and Business Media.

maximal responses of the other treatments were compared to this value.

Putative antagonists were tested by one of two protocols. The first was a conventional dose-response protocol, in the presence of the drug being tested for antagonism. In the second protocol, the glands were exposed to an agonist drug (usually a sub-maximal concentration) until there was no further increase in secretory rate. Then putative antagonist was tested (several concentrations) until an equilibrated rate of secretion was observed at each concentration. To test for reversal of antagonism, the glands were re-exposed to agonist alone for up to 30 min.

Inhibitory constants (K_i) were calculated from the following equation:

$$K_i = (\text{dose ratio} - 1) / [I],$$

where dose ratio is the ratio of the two agonist concentrations producing the same response in the presence and absence of the inhibitor, I (Goldstein et al., 1974).

Statistics

Unless otherwise stated, data are reported as mean \pm s.e.m. (N), and statistically analysed using one-way ANOVA or Student's *t*-tests.

Results

Agonists

The 11 ErAs tested in this study (Fig. 1) can be categorized arbitrarily into four groups on the basis of the responses obtained. (1) *Complete agonists* (Fig. 2) were those that stimulated the maximum response at or below the highest concentration tested. These were, in order of potency (approximate concentration eliciting 50% maximum response in parentheses): dihydroergotamine ($0.02 \mu\text{mol l}^{-1}$), ErN ($0.06 \mu\text{mol l}^{-1}$), methylergonovine ($0.1 \mu\text{mol l}^{-1}$), α -

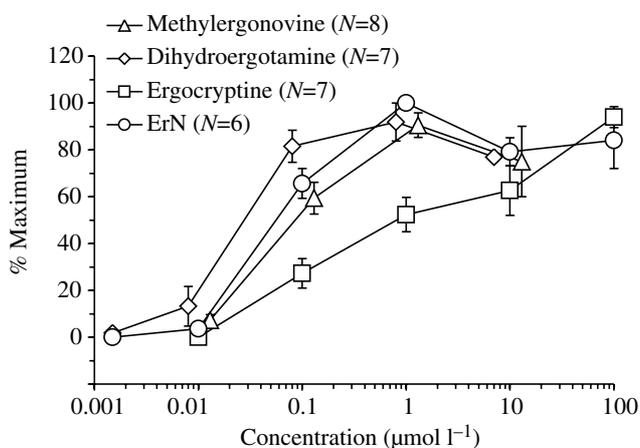


Fig. 2. Complete agonists. Dose-response curves for the indicated drugs were constructed as described in Materials and methods. The standard error of the mean (s.e.m.) is shown wherever it exceeds the size of the symbol.

ergocryptine ($0.9 \mu\text{mol l}^{-1}$). (2) *Incomplete agonists* were those that neither elicited the maximum response nor appeared to reach some plateaued response at the highest concentration that could be tested (usually because of limited availability). The approximate concentrations eliciting 20% maximum response were: ergocorninine ($3.5 \mu\text{mol l}^{-1}$), ergocristinine ($7.5 \mu\text{mol l}^{-1}$), and ergocristine ($10 \mu\text{mol l}^{-1}$; Fig. 3). (3) *Partial agonists* (Fig. 4) were those for which the response plateaued at substantially less than 100% of the maximum response. These were (with the approximate lowest concentration eliciting the respective maximum response in parentheses): ergocorninine (50% maximum by $1 \mu\text{mol l}^{-1}$), methysergide (28% maximum by $10 \mu\text{mol l}^{-1}$) and bromocryptine (22% maximum by $10 \mu\text{mol l}^{-1}$). (4) *Non-agonists*. Ergothioneine was the only ErA with no intrinsic activity at the highest concentration tested (seven glands tested up to 1mmol l^{-1}).

As mentioned in the Introduction, ErAs interact frequently with 5-HT and catecholamine receptors, behaving either as agonists or antagonists, but the natural ligand for the ErA-sensitive receptor in tick salivary glands has not yet been identified. The effect of 5-HT on tick salivary glands has been tested in a number of studies, and at best it is a very weak agonist (Kaufman and Phillips, 1973b; Kaufman, 1977; Needham and Sauer, 1975). We tested its action again as part of this study, with the hope of determining whether it acted *via* the DA receptor (blocked by butaclamol) or the ErA-sensitive receptor [blocked by sulphiride (Kaufman and Wong, 1983)]. Of 16 glands tested that responded to $10 \mu\text{mol l}^{-1}$ DA, only five were also stimulated by 5-HT (up to 10mmol l^{-1}); 5-HT was an incomplete agonist, with 20% maximum response occurring at $\sim 220 \mu\text{mol l}^{-1}$ (Fig. 3).

We asked whether this inconsistent and weak response to 5-HT might be due to high levels of monoamine oxidase (MAO) in the tissue. So we repeated some dose-response experiments with 5-HT in the presence of $220 \mu\text{mol l}^{-1}$ deprenyl, an MAO

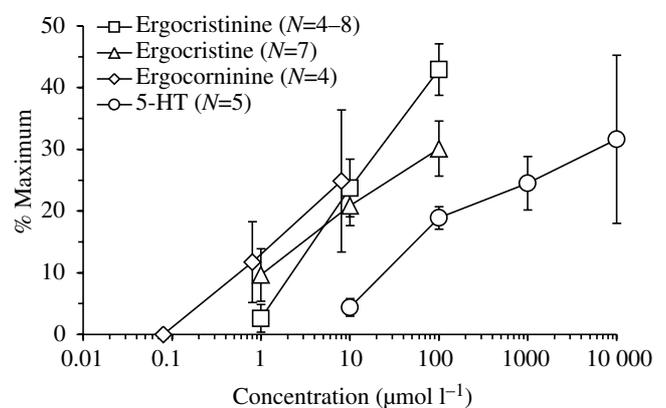


Fig. 3. Incomplete agonists. Dose-response curves for the indicated drugs were conducted as described in Materials and methods. The s.e.m. is shown wherever it exceeds the size of the symbol. The data for 5-hydroxytryptamine (5-HT) includes only those glands that showed some response to 5-HT.

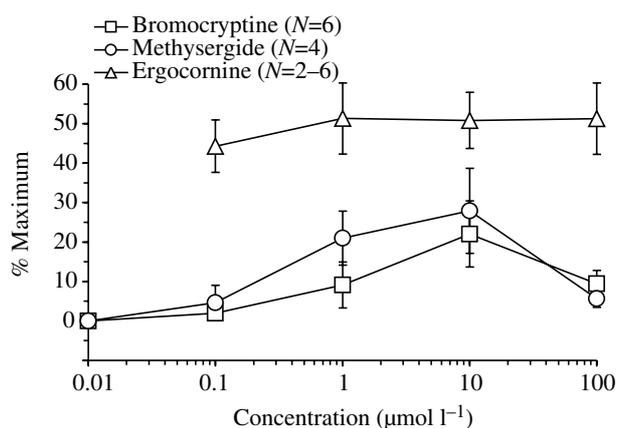


Fig. 4. Partial agonists. Dose-response curves for the indicated drugs were conducted as described in Materials and methods. The s.e.m. is shown wherever it exceeds the size of the symbol.

inhibitor known to be effective on tick salivary glands (Kaufman and Sloley, 1996). Even though MAO should have been almost completely inhibited under these conditions, 5-HT still failed to stimulate salivary fluid secretion in eight glands, all of which responded to 10 $\mu\text{mol l}^{-1}$ DA (data not shown). Thus we abandoned our attempt to determine at which receptor 5-HT elicits its weak, inconsistent effect.

Putative antagonists

Ergothioneine (non-agonist), bromocryptine and methysergide (partial agonists) were tested for their ability to inhibit ErN- and DA-stimulated secretion. Ergothioneine caused no rightward shift of the ErN dose-response curve (Fig. 5) nor of the DA dose-response curve (five trials; data not shown). Bromocryptine (3 trials) and methysergide (3 trials) did not significantly antagonize the action of DA (Fig. 6A), but both were effective, surmountable antagonists of ErN (Fig. 6B), with K_i s of $\sim 0.3 \mu\text{mol l}^{-1}$ (bromocryptine) and $\sim 11 \mu\text{mol l}^{-1}$ (methysergide).

DA and ErN have been demonstrated to act via distinct

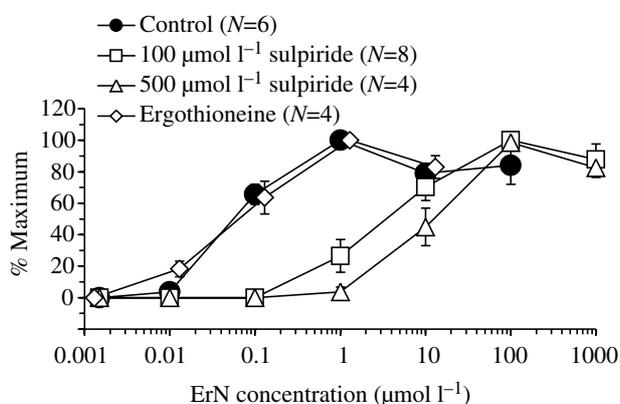


Fig. 5. Inhibition of ergonovine (ErN) by putative antagonists, ergothioneine and (+/-)-sulpiride. The s.e.m. is shown wherever it exceeds the size of the symbol.

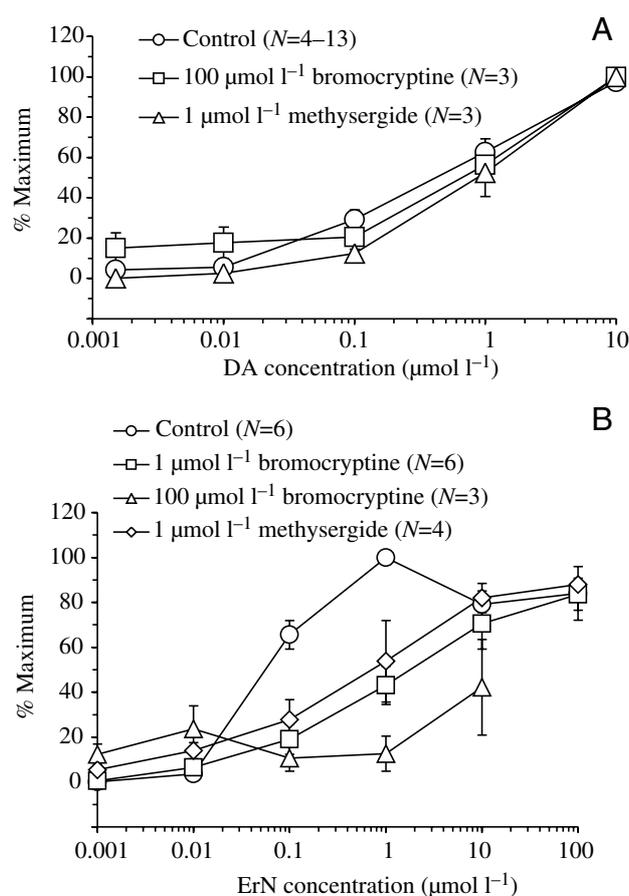


Fig. 6. Inhibition of (A) dopamine (DA) and (B) ergonovine (ErN) by the partial agonists, bromocryptine and methysergide. The s.e.m. is shown wherever it exceeds the size of the symbol.

receptors by the differential antagonism of sulpiride (Kaufman and Wong, 1983). We confirmed these findings here, determining an inhibitory constant of $\sim 0.73 \mu\text{mol l}^{-1}$ for sulpiride on ErN (Fig. 5), and an inability for sulpiride to attenuate the action of DA (data not shown).

Intracellular pathways

The intracellular pathways mediating DA-induced secretion involve cAMP, Ca^{2+} , cytosolic phospholipase A_2 (cPLA $_2$), and arachidonic acid (reviewed by Sauer et al., 2000; Bowman and Sauer, 2004). Nothing is known about the intracellular pathways mediating ErA-induced secretion. However, there is evidence that protein kinase C (PKC) is a component of the intracellular signalling pathway in tick salivary glands (see Discussion). So, in this study we tested the actions of a number of drugs known to stimulate or inhibit PKC in other systems to learn whether the action of DA and ErN were affected differently.

BIM (Toullec et al., 1991) and calphostin C (Kobayashi et al., 1989; Bruns et al., 1991) were tested for possible inhibitory effects, and OAG (Benz et al., 1992; Florin-Christensen et al., 1993) and DiC $_8$ (Lapetina et al., 1985) were tested for possible

excitatory effects on DA- and ErA-stimulated fluid secretion. Salivary glands were exposed to a sub-maximal concentration of DA ($0.1 \mu\text{mol l}^{-1}$) or ErN ($0.1 \mu\text{mol l}^{-1}$) for six 5-min readings to determine the equilibrated response at that concentration; the mean value (\pm s.e.m.) of the last two or three readings was recorded as the control response. Then the test drug (PKC activator or inhibitor) was added in the presence of DA or ErN and secretion was monitored for up to a further six 5-min readings. The glands were then re-exposed to either DA or ErN alone to record recovery. The results for the putative PKC activators, OAG and DiC₈, are presented in Table 1, and those for the putative PKC inhibitors, BIM and calphostin C, are presented in Table 2 and Fig. 7.

Neither OAG nor DiC₈ potentiated the action of sub-maximal concentrations of DA or ErN (Table 1). In all cases the secretory rates declined in the presence of OAG or DiC₈ and on return to the control treatment, but at least part of this reduction may have been the natural decline that occurs with time when glands are continually stimulated for extensive periods (Kaufman, 1976).

BIM did not inhibit the secretory response of salivary glands in the presence of sub-maximal ($0.1 \mu\text{mol l}^{-1}$) or supra-maximal ($10 \mu\text{mol l}^{-1}$) concentrations of ErN or DA (Table 2). The response to calphostin C depended on the concentration range. Low concentrations of calphostin C (10nmol l^{-1}) appeared to potentiate the action of DA (leftward shift of the dose-response curve; Fig. 7A) but not that of ErN (Fig. 7B). At $0.1 \mu\text{mol l}^{-1}$ calphostin C, there was no statistically significant inhibitory (or potentiating) effect using a sub-maximal ($0.1 \mu\text{mol l}^{-1}$) concentration of ErN or DA (Table 2).

Table 1. Effect of the protein kinase C activators on dopamine- and ergonovine-stimulated fluid transport by tick salivary glands

Treatment	% Maximum*	N	P†
OAG			
DA (control)	85.1 \pm 3.8	8	–
DA + OAG	79.9 \pm 4.4	8	0.382
Return to DA	63.8 \pm 4.4	8	0.002
ErN (control)	87.5 \pm 2.2	7	–
ErN + OAG	72.4 \pm 9.9	7	0.183
Return to ErN	55.4 \pm 10.8	7	0.025
DiC₈			
DA (control)	78.6 \pm 3.5	8	–
DA + DiC ₈	50.6 \pm 6.0	10	0.001
Return to DA	43.4 \pm 6.5	4	0.005
ErN (control)	78.6 \pm 4.8	9	–
ErN + DiC ₈	59.2 \pm 3.0	9	0.004
Return to ErN	41.6 \pm 2.9	9	0.0000

OAG, 1-oleoyl-2-acetyl-sn-glycerol ($100 \mu\text{mol l}^{-1}$); DiC₈, 1,2-dioctanoyl-sn-glycerol ($100 \mu\text{mol l}^{-1}$); DA, dopamine ($0.1 \mu\text{mol l}^{-1}$); ErN, ergonovine ($0.1 \mu\text{mol l}^{-1}$).

*% Maximum is calculated from the maximum rate recorded during each initial control period (\pm s.e.m.).

†Student's *t*-test (cf control).

Ion transport inhibitors

Furosemide [an inhibitor of various Cl⁻ cotransporter systems (Cabantchik and Greger, 1992)] and amiloride [an inhibitor of many Na⁺ transport systems (Kleyman and Cragoe, Jr, 1988)] were both tested for effects on DA- and ErN-stimulated secretion. Salivary glands were exposed to $10 \mu\text{mol l}^{-1}$ DA or $10 \mu\text{mol l}^{-1}$ ErN until maximum secretion was achieved. They were then exposed to DA or ErN along with $1 \mu\text{mol l}^{-1}$ to 1mmol l^{-1} furosemide or amiloride for three successive readings of 5 min for each concentration. Neither furosemide nor amiloride had any significant effect on DA- or ErN-stimulated secretory rates; note, however, that the sample sizes were small (Table 3).

Discussion

The multiple agonist and antagonist actions of ErAs in systems other than the tick salivary gland (most studies are on mammals) are mediated predominantly, if not exclusively, *via* various catecholamine and tryptamine receptors (Berde and Schild, 1978; Goldstein et al., 1980; Pertz and Eich, 1999). Most studies on insects and other invertebrates conform to vertebrate models in this respect (e.g. Sakharov et al., 1989; Wedemeyer et al., 1992; Blenau et al., 1998; Degen et al., 2000). However, 5-HT is only a very weak agonist at best for stimulating fluid secretion in tick salivary glands (Kaufman and Phillips, 1973b; Needham and Sauer, 1975; Kaufman, 1977) (this study). Evidence for a DA receptor (a D-1 type), however, is considerable (for reviews, see Sauer et al., 2000; Bowman and Sauer, 2004). As mentioned in the Introduction, ErAs do not exert their effects *via* this receptor. In brief, the ErA effects on the tick salivary gland cannot be interpreted in the same light as ErA effects in most other systems. There seem to be only very few other examples in the literature in which an ErA might act *via* an unidentified receptor (den Boer et al., 1991).

In this study, the ErAs tested fell into one of four classes, grouped arbitrarily according to their efficacy at the ErA-sensitive receptor: complete agonists, incomplete agonists, partial agonists and non-agonists. The structures of the ErAs tested are shown in Fig 1. Those that exhibited at least some agonist activity (all except ergothioneine) are based on an ergoline ring structure. Although ergotamine was not tested here, it has also been reported as a full agonist, with a potency similar to that of ergonovine (Kaufman, 1977). There is little beyond that broad generalization, however, to explain the other differences in activity presented here. For example, only three of the five complete agonists are ergopeptines (ergotamine, dihydroergotamine and α -ergocriptine), the other two (ErN and methylergonovine) are not. Moreover, with the exception of methysergide, all of the incomplete and partial agonists are also ergopeptines (ergocornine, ergocorninine, ergocristine, ergocristinine and bromocriptine).

It is commonly observed that the action of ErAs is difficult to reverse even with extensive washout procedures (Bond et al., 1989; Schöning et al., 2001), and **this was found to be the**

Table 2. Effect of the protein kinase C inhibitors, bisindolymaleimide and calphostin C on ergonovine- and dopamine-stimulated fluid transport by tick salivary glands

Treatment	% Maximum*	N	P [†]
BIM			
10 $\mu\text{mol l}^{-1}$ ErN (control)	82.3 \pm 3.1	5	–
10 $\mu\text{mol l}^{-1}$ ErN + 0.1 $\mu\text{mol l}^{-1}$ BIM	79.9 \pm 3.0	5	0.589
10 $\mu\text{mol l}^{-1}$ ErN + 0.3 $\mu\text{mol l}^{-1}$ BIM	93.5 \pm 10.4	5	0.343
10 $\mu\text{mol l}^{-1}$ ErN + 1.0 $\mu\text{mol l}^{-1}$ BIM	79.3 \pm 11.2	4	0.810
0.1 $\mu\text{mol l}^{-1}$ ErN (control)	82.7 \pm 2.0	4	–
0.1 $\mu\text{mol l}^{-1}$ ErN + 0.2 $\mu\text{mol l}^{-1}$ BIM	105 \pm 14.6	4	0.227
Return to 0.1 $\mu\text{mol l}^{-1}$ ErN	66.0 \pm 3.2	3	0.015
0.1 $\mu\text{mol l}^{-1}$ DA (control)	87.2 \pm 4.8	4	–
0.1 $\mu\text{mol l}^{-1}$ DA + 0.2 $\mu\text{mol l}^{-1}$ BIM	97.1 \pm 14.4	4	0.554
Return to 0.1 $\mu\text{mol l}^{-1}$ DA	108 \pm 7.8	3	0.095
Calphostin C			
0.1 $\mu\text{mol l}^{-1}$ ErN (control)	83.9 \pm 2.9	5	–
0.1 $\mu\text{mol l}^{-1}$ ErN + 0.1 $\mu\text{mol l}^{-1}$ calphostin C	90.5 \pm 3.6	5	0.194
Return to 0.1 $\mu\text{mol l}^{-1}$ ErN	48.9 \pm 0.5	2	0.0002
0.1 $\mu\text{mol l}^{-1}$ DA (control)	82.7 \pm 4.1	6	–
0.1 $\mu\text{mol l}^{-1}$ DA + 0.1 $\mu\text{mol l}^{-1}$ calphostin C	106 \pm 10.1	6	0.077
Return to 0.1 $\mu\text{mol l}^{-1}$ DA	104 \pm 17.7	5	0.398

BIM, bisindolymaleimide; DA, dopamine; ErN, ergonovine.

*% Maximum is calculated from the maximum rate recorded during each initial control period (\pm s.e.m.).

[†]Student's *t*-test (cf control).

case with the tick salivary gland. One potential explanation for the long-lasting effect is continual diffusion from a pool of drug absorbed into the tissue during the incubation period (Bulow et al., 1986; Tfelt-Hansen and Johnson, 1993).

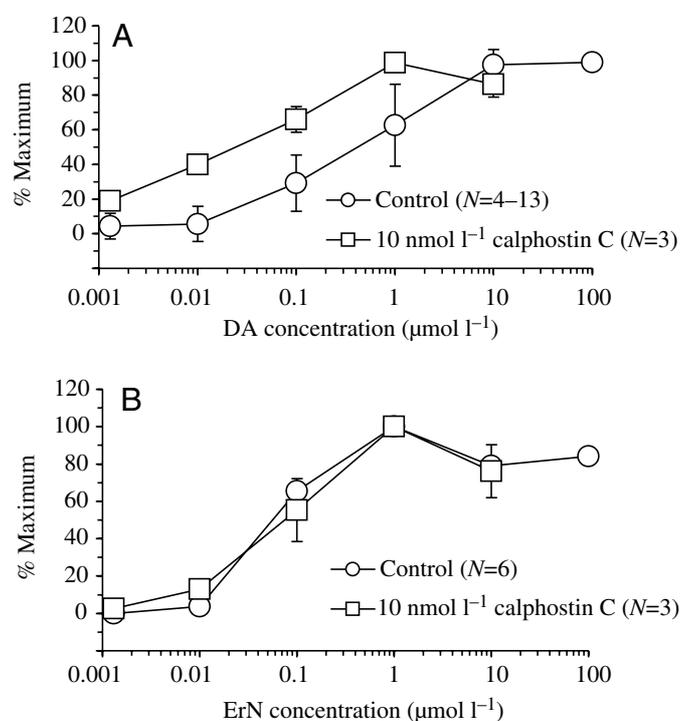


Fig. 7. Potentiation of (A) dopamine (DA) but not (B) ergonovine (ErN) by the putative PKC inhibitor calphostin C. The s.e.m. is shown wherever it exceeds the size of the symbol.

Berridge and Prince (Berridge and Prince, 1973), reporting on the agonist action of LSD at the blowfly salivary gland 5-HT receptor, discounted the latter possibility for that system. They proposed instead that part of the ErA molecule (presumably the diethyl amide) binds tightly to an allosteric site of the 5-HT receptor, allowing the active portion (presumably the ergoline) to repeatedly attach to and disengage from the active site. Similar to the blowfly salivary gland, the tick salivary gland is free of layers of muscle or connective tissue that could serve to store a pool of drug (although extrinsic fat body tissue is omnipresent). In rat tail artery preparations, insurmountable blockade of the 5-HT response by methysergide has been attributed to allosteric modulation of 5-HT_{2A} receptors rather than to pseudoirreversible inhibition (Pertz and Eich, 1992). In this case, however, (unlike that for the blowfly and tick salivary glands), onset of action is also very prolonged (Schöning et al., 2001). A general model has been proposed whereby one can differentiate between slow ligand-receptor dissociation from slow diffusion (Martin et al., 1995).

The results presented here further support earlier observations that 5-HT is unlikely to be the endogenous ligand at the ErA-sensitive receptor. The small and inconsistent effect of 5-HT might be due to an indirect action. For example, tick salivary glands contain a relatively high endogenous content of DA (Kaufman and Sloley, 1996), possibly in the numerous granular cells. Perhaps the inconsistent agonist action of 5-HT is due to an occasional stimulation of DA release from this endogenous source.

There is now a growing understanding about the intracellular signalling cascade following stimulation of the tick (*Amblyomma americanum*) salivary gland DA receptor

Table 3. *Effect of amiloride and furosemide on dopamine- and ergonovine-stimulated fluid transport by tick salivary glands*

Treatment	% Maximum*	N	P†
Amiloride			
DA (control)	100±0	6	–
DA + 1 µmol l ⁻¹ amiloride	108±6.9	3	0.369
DA + 10 µmol l ⁻¹ amiloride	104±15.0	3	0.832
DA + 100 µmol l ⁻¹ amiloride	99.8±11.1	6	0.986
DA + 1 mmol l ⁻¹ amiloride	98.4±13.6	2	0.925
DA + 10 mmol l ⁻¹ amiloride	83.7±28.3	2	0.667
ErN (control)	100±0	2	–
ErN + 1 µmol l ⁻¹ amiloride	112±22.6	2	0.701
ErN + 10 µmol l ⁻¹ amiloride	112±12.4	2	0.500
ErN + 100 µmol l ⁻¹ amiloride	94.3±15.3	2	0.642
Furosemide			
DA (control)	100±0	2	–
DA + 1 µmol l ⁻¹ furosemide	123±11.8	2	0.218
DA + 10 µmol l ⁻¹ furosemide	134±0	2	–
DA + 100 µmol l ⁻¹ furosemide	122±0	2	–
DA + 1 mmol l ⁻¹ furosemide	131±3.1	2	0.063
ErN (control)	100±0	3	–
ErN + 1 µmol l ⁻¹ furosemide	104±2.7	3	0.190
ErN + 10 µmol l ⁻¹ furosemide	102±2.3	3	0.765
ErN + 100 µmol l ⁻¹ furosemide	96.8±9.4	3	0.684

DA, dopamine (10 µmol l⁻¹); ErN, ergonovine (10 µmol l⁻¹).

*% Maximum is calculated from the maximum rate recorded during each initial control period (± s.e.m.).

†Student's *t*-test (cf control).

(reviewed by Sauer et al., 2000; Bowman and Sauer, 2004). The salivary gland contains several isoforms of a cAMP-dependent protein kinase (cAPKC₁₋₃) that are activated in isolated salivary glands exposed to DA. As a result, at least a dozen salivary gland proteins are phosphorylated. The glands also contain phosphoprotein phosphatase activity, further supporting a role for PKC in salivary fluid secretion. Under the conditions tested here, there is little evidence to suggest that PKC is an intermediate in the pathway linked to the ErA-sensitive receptor or the DA receptor. The two PKC activators, OAG and DiC₈, did not stimulate salivary fluid secretion on their own (data not shown), and they did not potentiate the stimulatory effect of sub-maximal concentrations of DA or ErN (both at 0.1 µmol l⁻¹; Table 1). The PKC inhibitors, BIM and calphostin C, likewise did not inhibit the stimulatory action of 0.1 µmol l⁻¹ DA or ErN (Table 2); if anything, the trend was to potentiate the action of DA and ErN, though the differences between control and treated samples in Table 2 were not statistically significant in a consistent manner. The potentiating trend was also observed at lower concentrations of calphostin C, where 10 nmol l⁻¹ appeared to shift the dose–response curve of DA to the left, but not that of ErN (Fig. 7); the number of replicates in this experiment, however, was small. This matter clearly merits further investigation.

We have some confidence that the experimental protocol used for the PKC experiments was appropriate, both with regard to the concentration ranges tested and the duration of incubation. **Just a few examples include:** PKC mediation in 5-HT stimulated ciliary beat frequency in embryos of the pond snail, *Heliosoma*

trivolis (Christopher et al., 1999), inhibition of PKC by BIM in chick proximal tubule (Dudas et al., 2002), activation of PKC in rabbit portal vein myocytes (Albert and Large, 2001), stimulation of PKC of human kidney proximal tubules (Pietig et al., 2001), and inhibition of PKC by calphostin C on human endothelial cells (Orzechowski et al., 2001).

Our knowledge of the pharmacological properties of the tick ErA-sensitive receptor is obviously rudimentary compared to that of many mammalian systems, at least in part because relatively few congeners have been tested. Recently it has been shown that 8R-lisuride is a partial agonist at human histamine H₁ receptors (Bakker et al., 2004), which expands the repertoire of ErA targets yet further. However, histamine (up to 1 mmol l⁻¹) did not stimulate fluid secretion in tick salivary glands (Kaufman, 1977). Unfortunately, we still have no idea as to what the natural ligand is at the tick salivary gland ErA-sensitive receptor, or whether it is a component of a neuronal or hormonal pathway. We also do not know the physiological conditions under which this pathway to fluid secretion is stimulated [the DA pathway seems to be involved in haemolymph volume regulation (Kaufman et al., 1980)]. This remains a major gap in our understanding of tick salivary gland function.

List of abbreviations

5-HT	5-hydroxytryptamine
BIM	bisindolymaleimide
cPLA ₂	cytosolic phospholipase A ₂

DA	dopamine
DiC ₈	1,2-dioctanoyl- <i>sn</i> -glycerol
ErA	ergot alkaloid
ErN	ergonovine
GABA	γ-aminobutyric acid
MAO	monoamine oxidase
OAG	1-oleoyl-2-acetyl- <i>sn</i> -glycerol
PKC	protein kinase C

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References

- Albert, A. P. and Large, W. A. (2001). Comparison of spontaneous and noradrenaline-evoked non-selective cation channels in rabbit portal vein myocytes. *J. Physiol.* **530**, 457-468.
- Bakker, R. A., Weiner, D. M., ter Laak, T., Beuming, T., Zuiderveld, O. P., Edelbroek, M., Hacksell, U., Timmerman, H., Brann, M. R. and Leurs, R. (2004). 8R-Lisuride is a potent stereospecific histamine H₁-receptor partial agonist. *Mol. Pharmacol.* **65**, 538-549.
- Benz, I., Herzig, J. W. and Kohlhardt, M. (1992). Opposite effects of angiotensin II and the protein kinase C activator OAG on cardiac Na⁺ channels. *J. Membr. Biol.* **130**, 183-190.
- Berde, B. (1980). Ergot compounds: a synopsis. In *Ergot Compounds and Brain Function* (ed. M. Goldstein, A. Lieberman, D. M. Calne and M. O. Thorner), pp. 3-23. New York: Raven Press.
- Berde, B. and Schild, H. O. (1978). *Ergot Alkaloids and Related Compounds*. Berlin, Heidelberg, New York: Springer-Verlag.
- Berridge, M. J. and Prince, W. T. (1973). Mode of action of hallucinogenic molecules. *Nat. New Biol.* **243**, 283-284.
- Blenau, W., Erber, J. and Baumann, A. (1998). Characterization of a dopamine D1 receptor from *Apis mellifera*: cloning, functional expression, pharmacology, and mRNA localization in the brain. *J. Neurochem.* **70**, 15-23.
- den Boer, M. O., Heiligers, J. P. and Saxena, P. R. (1991). Carotid vascular effects of ergotamine and dihydroergotamine in the pig: no exclusive mediation via 5-HT₁-like receptors. *Br. J. Pharmacol.* **104**, 183-189.
- Bond, R. A., Ornstein, A. G. and Clarke, D. E. (1989). Unsurmountable antagonism to 5-hydroxytryptamine in rat kidney results from pseudoirreversible inhibition rather than multiple receptors or allosteric receptor modulation. *J. Pharmacol. Exp. Ther.* **249**, 401-410.
- Bowman, A. S. and Sauer, J. R. (2004). Tick salivary glands: function, physiology and future. *Parasitology* **129**, S67-S81.
- Bruns, R. F., Miller, D., Merriman, R. L., Howbert, J. J., Heath, W. F., Kobayashi, E., Takahashi, I., Tamaoki, T. and Nakano, H. (1991). Inhibition of protein kinase C by calphostin C is light-dependent. *Biochem. Biophys. Res. Commun.* **176**, 288-293.
- Bulow, P. M., Ibraheem, J. J., Paalzow, G. and Tfelt-Hansen, P. (1986). Comparison of pharmacodynamic effects and plasma levels of oral and rectal ergotamine. *Cephalalgia* **6**, 107-111.
- Cabantchik, Z. I. and Greger, R. (1992). Chemical probes for anion transporters of mammalian cell membranes. *Am. J. Physiol.* **262**, C803-C827.
- Christopher, K. J., Young, K. G., Chang, J. P. and Goldberger, J. I. (1999). Involvement of protein kinase C in 5-HT stimulated ciliary activity in *Heliosoma trivolvris* embryos. *J. Physiol.* **515**, 511-522.
- Degen, J., Gewecke, M. and Roeder, T. (2000). The pharmacology of a dopamine receptor in the locust nervous tissue. *Eur. J. Pharmacol.* **396**, 59-65.
- Dudas, P. L., Villalobos, A. R., Gocek-Sutterlin, G., Laverty, G. and Renfro, J. L. (2002). Regulation of transepithelial phosphate transport by PTH in chicken proximal tubule epithelium. *Am. J. Physiol. Regul. Integr. Comp. Physiol.* **282**, R139-R146.
- Florin-Christensen, J., Florin-Christensen, M., Delfino, J. M. and Rasmussen, H. (1993). New patterns of diacylglycerol metabolism in intact cells. *Biochem. J.* **389**, 783-788.
- Goldstein, A., Aranow, L. and Kalman, S. M. (1974). *Principles of Drug Action: The Basis of Pharmacology* (2nd edn). New York: John Wiley and Sons.
- Goldstein, M., Lieberman, A., Calne, D. B. and Thorner, M. O. (1980). *Ergot Compounds and Brain Function: Neuroendocrine and Neuropsychiatric Aspects*. New York: Raven Press.
- Kaufman, W. R. (1976). The influence of various factors on fluid secretion by in vitro salivary glands of ixodid ticks. *J. Exp. Biol.* **64**, 727-742.
- Kaufman, W. R. (1977). The influence of adrenergic agonists and their antagonists on fluid secretion by isolated salivary glands of ixodid ticks. *Eur. J. Pharmacol.* **45**, 61-68.
- Kaufman, W. R. (1989). Tick-host interaction: a synthesis of current concepts. *Parasitol. Today* **5**, 47-56.
- Kaufman, W. R. and Phillips, J. E. (1973a). Ion and water balance in the ixodid tick, *Dermacentor andersoni*. I. Routes of ion and water excretion. *J. Exp. Biol.* **58**, 523-536.
- Kaufman, W. R. and Phillips, J. E. (1973b). Ion and water balance in the ixodid tick, *Dermacentor andersoni*. II. Mechanisms and control of salivary secretion. *J. Exp. Biol.* **58**, 537-547.
- Kaufman, W. R. and Sloley, B. D. (1996). Catabolism of dopamine and 5-hydroxytryptamine by monoamine oxidase in the ixodid tick, *Amblyomma hebraeum*. *Insect Biochem. Mol. Biol.* **26**, 101-109.
- Kaufman, W. R. and Wong, D. L. (1983). Evidence for multiple receptors mediating fluid secretion in salivary glands of ticks. *Eur. J. Pharmacol.* **87**, 43-52.
- Kaufman, W. R., Aeschlimann, A. and Diehl, P. A. (1980). Regulation of body volume by salivation in a tick challenged with fluid loads. *Am. J. Physiol.* **238**, R102-R112.
- Kleyman, T. R. and Cragoe, E. J., Jr (1988). Amiloride and its analogs as tools in the study of ion transport. *J. Membr. Biol.* **105**, 1-21.
- Kobayashi, E., Nakano, H., Morimoto, M. and Tamaoki, T. (1989). Calphostin C (UNC-1028C), a novel microbial compound, is a highly potent and specific inhibitor of protein kinase C. *Biochem. Biophys. Res. Commun.* **159**, 548-553.
- Lapetina, E. G., Reep, B., Ganong, B. R. and Bell, R. M. (1985). Exogenous *sn*-1,2-diacylglycerols containing saturated fatty acids function as bioregulators of protein kinase C in human platelets. *J. Biol. Chem.* **260**, 1358-1361.
- Lindsay, P. J. and Kaufman, W. R. (1986). Potentiation of salivary fluid secretion in ixodid ticks: a new receptor system for γ-aminobutyric acid. *Can. J. Physiol. Pharmacol.* **64**, 1119-1126.
- Martin, G. R., Martin, R. S. and Wood, J. (1995). Long-acting 5-HT_{1D} receptor agonist effects of dihydroergotamine: studies using a model to differentiate slow drug-receptor dissociation from diffusion. In *Experimental Headache Models* (ed. J. Olesen and M. A. Moskowitz), pp. 163-167. Philadelphia: Lippincott-Raven.
- Needham, G. and Sauer, J. R. (1975). Control of fluid secretion by isolated salivary glands of the lone star tick. *J. Insect Physiol.* **21**, 1893-1898.
- Orzechowski, H. D., Gunther, A., Menzil, S., Zimmermann, A., Funke-Kaiser, H., Real, R., Subkowski, T., Zollmann, F. S. and Paul, M. (2001). Transcriptional mechanism of protein kinase C-induced isoform-specific expression of the gene for endothelin-converting enzyme-1 in human endothelial cells. *Mol. Pharmacol.* **60**, 1332-1342.
- Peroutka, S. J. (1996). Drugs effective in the therapy of migraine. In *Goodman and Gilman's Pharmacological Basis of Therapeutics* (ed. P. B. Molinoff and R. W. Rudden), pp. 487-503. New York: McGraw-Hill.
- Pertz, H. and Eich, E. (1992). O-Acylated lysergol and dihydrolysergol-I derivatives as competitive antagonists of 5-HT at 5-HT₂ receptors of rat tail artery: allosteric modulation instead of pseudoirreversible inhibition. *Naunyn-Schmiedeberg's Arch. Pharmacol.* **345**, 394-401.
- Pertz, H. and Eich, E. (1999). Ergot alkaloids and their derivatives as ligands for serotonergic, dopaminergic and adrenergic receptors. In *Ergot: The genus Claviceps* (ed. V. Kren and L. Cvak), pp. 411-440. Amsterdam: Harwood Academic Publishers.
- Pietig, G., Mehrens, T., Hirsch, J. R., Cetinkaya, I., Piechota, H. and Schlatter, E. (2001). Properties and regulation of organic cation transport in freshly isolated human proximal tubules. *J. Biol. Chem.* **276**, 33741-33746.
- Sakharov, D. A., Hiripi, L. and Salánki, J. (1989). Pharmacologically induced stereotyped locomotory movements in the pelecypod mollusk, *Anodonta cygnea*. *Comp. Biochem. Physiol.* **92C**, 343-347.
- Sauer, J. R., Essenberg, R. C. and Bowman, A. S. (2000). Salivary glands

- in ixodid ticks: control and mechanism of secretion. *J. Insect Physiol.* **46**, 1069-1078.
- Schmidt, S. P., Essenberg, R. C. and Sauer, J. R.** (1981). Evidence for a D1 dopamine receptor in the salivary glands of *Amblyomma americanum* (L.) *J. Cyclic Nucleotide Res.* **7**, 375-384.
- Schmidt, S. P., Essenberg, R. C. and Sauer, J. R.** (1982). Dopamine sensitive adenylate cyclase in the salivary glands of the lone star tick. *Comp. Biochem. Physiol.* **72**, 9-14.
- Schöning, C., Flieger, M. and Pertz, H. H.** (2001). Complex interaction of ergovaline with 5-HT_{2A}, 5-HT_{1B/1D}, and alpha₁ receptors in isolated arteries of rat and guinea pig. *J. Anim. Sci.* **79**, 2202-2209.
- Tfelt-Hansen, P. and Johnson, E. S.** (1993). Ergotamine. In *The Headaches* (ed. J. Olesen, P. Tfelt-Hansen and K. M. Welch), pp. 313-322. New York: Raven Press.
- Toullec, D., Pianetti, P., Coste, H., Bellevergue, P., Grand-Perret, T., Ajakane, M., Baudet, V., Boissin, P., Boursier, E., Loriolle, F. et al.** (1991). The bisindolylmaleimide GF 109203X is a potent and selective inhibitor of protein kinase C. *J. Biol. Chem.* **266**, 15771-15781.
- Wedemeyer, S., Roeder, T. and Gewecke, M.** (1992). Pharmacological characterization of a 5HT receptor in locust nervous tissue. *Eur. J. Pharmacol.* **223**, 173-178.
- Wong, D. L. and Kaufman, W. R.** (1981). Potentiation by spiperone and other butyrophenones of fluid secretion by isolated salivary glands of ixodid ticks. *Eur. J. Pharmacol.* **73**, 163-173.