REVIEW

Molecular Pharmacology of T-type Ca^{2+} Channels

Tiffany N. Heady¹, Juan C. Gomora², Timothy L. Macdonald¹ and Edward Perez-Reyes^{2,*}

¹Department of Chemistry, University of Virginia, Charlottesville, Virginia 22904, USA

²Department of Pharmacology, University of Virginia, Charlottesville, Virginia 22908, USA

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ABSTRACT—Over the past few years increasing attention has been focused on T-type calcium channels and their possible physiological and pathophysiological roles. Efforts toward elucidating the exact role(s) of these calcium channels have been hampered by the lack of T-type specific antagonists, resulting in the subsequent use of less selective calcium channel antagonists. In addition, the activity of these blockers often varies with cell or tissue type, as well as recording conditions. This review summarizes a variety of compounds that exhibit varying degrees of blocking activity towards T-type Ca^{2+} channels. It is designed as an aid for researchers in need of antagonists to study the biophysical and pathological nature of T-type channels, as well as a starting point for those attempting to develop potent and selective antagonists of the channel.

Keywords: T-type calcium channel, Antihypertensive, Mibefradil, Antiepileptic, Anesthetic, Antipsychotic, Amiloride

Introduction

Calcium is essential for life and is the most common signal transduction element in cells. A staggering electrochemical gradient exists between its extracellular concentration of approximately 2 mM compared to resting intracellular concentrations of approximately 100 nM. Stimulation of cells can lead to increases in intracellular concentrations into the micromolar range, with much higher concentrations in microdomains. This calcium enters the cytosol either through plasma membrane ion channels or is released from intracellular pools. Plasma membrane ion channels can be classified as either receptor- or store-operated channels, which are usually non-selective for cations such as Na^+ and Ca^{2+} , or voltage-gated channels, which are highly selective for Ca^{2+} .

The diversity of voltage-gated calcium channels has been extensively studied using electrophysiological, biochemical, pharmacological, and more recently, using molecular biology techniques. Early voltage-clamp studies identified two main classes of channels: those that responded to small (10 mV) changes in the resting membrane potential, or low-voltage-activated (LVA), and those that required stronger (30 mV) depolarizations to open, or high-voltage-activated (HVA). Pharmacological studies allowed further dissection

of the HVA family into L-, N-, P-, Q-, and R-types (1). These studies relied heavily on toxins isolated from snails (*Conus*) and funnel-web spiders (*Agelenopsis*) (2). Cloning of ten $\alpha 1$ subunits of voltage-activated Ca^{2+} channels has allowed a new classification based on sequence similarities (3). Alignments reveal that there are three main subfamilies of $\alpha 1$ subunit: 1) $\text{Ca}_v 1$, which contains four members that encode L-type channels ($\text{Ca}_v 1.1$, $\alpha 1\text{S}$; $\text{Ca}_v 1.2$, $\alpha 1\text{C}$; $\text{Ca}_v 1.3$, $\alpha 1\text{D}$; and $\text{Ca}_v 1.4$, $\alpha 1\text{F}$, which has yet to be expressed); 2) $\text{Ca}_v 2$, which contains three members including the P- and Q-types (both encoded by $\text{Ca}_v 2.1$, $\alpha 1\text{A}$), the N-type ($\text{Ca}_v 2.2$, $\alpha 1\text{B}$), and R-type ($\text{Ca}_v 2.3$, $\alpha 1\text{E}$); and 3) $\text{Ca}_v 3$, which contains three members that encode T-type channels ($\text{Ca}_v 3.1$, $\alpha 1\text{G}$; $\text{Ca}_v 3.2$, $\alpha 1\text{H}$; and $\text{Ca}_v 3.3$, $\alpha 1\text{I}$). All of these $\alpha 1$ subunits contain structural motifs that have been extremely conserved during evolution. The most basic element appears to be a pore loop surrounded by two membrane spanning domains (4). During evolution, more membrane spanning regions were added, resulting in a structure containing 6 transmembrane regions and a pore loop. One of these transmembrane regions contains many positive charges, conferring voltage sensitivity to the channel. Such is the structure of many voltage-gated K^+ channels (K_v), which are composed of four of these subunits. The next step in evolution was to join four α subunits into a single molecule, which is the structure of both voltage-gated Ca^{2+} and Na^+ channels. This conservation of sequence and predicted

*Corresponding author: FAX: +1-804-982-3878

E-mail: eperez@virginia.edu

structure allows comparisons of these channels to the *Streptomyces* K⁺ channel whose structure was recently solved using X-ray crystallography (4). Such comparisons may be useful in understanding drug binding sites (5).

Biochemical studies established that HVA channels contain auxiliary subunits such as α_2 , β , δ , and γ . Subsequent studies showed that δ was encoded on the same gene as α_2 . Molecular cloning has revealed that each of these subunits contains other family members. There are now genes for three $\alpha_2\delta$ subunits, four β subunits and five γ subunits (6, 7). Coexpression studies of the cloned subunits indicates that auxiliary subunits can alter the pharmacological properties of the channel (8). Furthermore, auxiliary subunits themselves may be the target of drugs; for example, gabapentin binds with high affinity to $\alpha_2\delta$ (9). The structure of LVA channels has not been determined biochemically.

Although the subject of this review is the pharmacology of T-type calcium channels, it should be noted that presently there are no compounds that are highly selective for these channels. Studies on the pharmacology of T-type channels have been complicated by many factors. For one, these channels are rarely expressed alone, which means the currents can be contaminated by other ionic conductances, notably HVA channels. This leads to under-estimates of the drug's potency. Typically LVA currents are separated from HVA currents by changing the holding potential from -90 mV (where both are active) to -40 mV where only some HVA channels are active. However, the block of many ion channels is state-dependent, with up to 1000-fold higher affinity for partially inactivated states. This may also lead to under-estimates of a drug's selectivity because the effects are being measured on LVA channels in the resting state, while HVA channels may be partially inactivated. Most of the studies reported herein used resting membrane potentials ranging from -100 to -80 mV, so the reported IC₅₀ values are probably dominated by the affinity of the drug for the resting state. Second, T-type channels are typically expressed at low densities, so many studies have used high concentrations of charge carrier to amplify the small currents. Again, this may lead to under-estimates of potency because channel block is often reduced at high divalent cation concentrations. Although this effect is often attributed to interactions in the permeation pathway, it should be noted that surface charge screening may also play a role. Due to these considerations, the divalent cation and its concentration are noted in the tables.

Antihypertensives

Calcium channel blockers have been used since the early 1960s to treat a variety of cardiovascular diseases like hypertension, cardiac arrhythmia and angina pectoris (10). Traditional calcium channel antagonists fit into three distinct chemical classes, the phenylalkylamines (e.g., vera-

pamil), dihydropyridines (e.g., nifedipine) and benzothiazepines (e.g., diltiazem). Representative structures are shown in Fig. 1. In general, their beneficial effects are thought to be due to blocking smooth muscle L-type channels, leading to decreases in cytosolic Ca²⁺, and relaxation of vascular smooth muscle cells. An important property of these drugs is to block preferentially smooth muscle L-type channels with little effect on cardiac L-type channels. Many first generation calcium channel blockers blocked both, such as verapamil and diltiazem. Second generation blockers such as nimodipine display greater selectivity for vascular beds (11). Two mechanisms that contribute to this selectivity are: 1) state dependent block, where drugs preferentially block partially inactivated channels, and 2) tissue specific expression of Ca_v1.2 splice variants that have distinct sensitivity to the drugs (12).

Mibefradil (Ro 40-5967) was introduced to the market in 1997, but then abruptly withdrawn. It was approved for use in hypertension and angina and marketed as the first selective T-type Ca²⁺ channel blocker (13). Indeed, depending on the cell type, mibefradil blocks T-type Ca²⁺ channels 10 to 30 times more potently than L-type Ca²⁺ channels (14, 15). In addition, mibefradil is highly tissue selective, relaxing smooth muscle without inducing reflex tachycardia, or having much effect on cardiac chronotropy or inotropy (13, 16). However, pharmacokinetic interactions with other drugs metabolized by cytochromes P-450 3A4 and 2D6 (antihistamines, such as astemizole) eventually led to the withdrawal of mibefradil from the clinic.

Electrophysiological experiments in a wide variety of native T-type Ca²⁺ currents have shown mibefradil IC₅₀ values ranging from 0.1 to 4.7 μ M (Table 1). Vascular smooth muscle T-type currents have been the most sensitive to mibefradil with an IC₅₀ of 0.1–0.2 μ M (14). In contrast, T-type currents recorded from mouse spermatogenic cells were reported to be much less sensitive (IC₅₀ = 4.7 μ M (17)). Mibefradil blocks all three cloned T-type channels with similar potency (18), although Ca_v3.3 may be twofold less sensitive (19). Direct comparisons indicate that it blocks native and the cloned Ca_v3.2 channels with equal potency (20).

Mibefradil can also block HVA channels. In cultured spinal motoneurons, mibefradil blocked N, L-, and P/Q-type channels at similar concentrations (1.4 μ M) as the block of an LVA current (21). In cerebellar Purkinje neurons, mibefradil blocked P-type currents with an apparent IC₅₀ of 3 μ M; however, under identical conditions, it blocked T-type currents with an IC₅₀ of 14 nM (22). The major difference in these studies was the holding potential, which was -90 mV in the motoneuron study and -70 mV in the Purkinje neuron study. Although this discrepancy could be caused by differences in voltage-dependent block (discussed below), this does not appear to be the case (23).

Fig. 1. Calcium channel blockers that also inhibit T-type channels.

Table 1. Calcium channel blockers that also inhibit T-type channels

	Mibefradil	Verapamil	D600	Amlodipine	Nimodipine	Isradipine	Nifedipine	Nicardipine	Flunarizine	Diltiazem	Reference
Hypothalamus			50		7		5	3.5	0.7	70	(32)
Amygdala neurons			65					2.5	1.1	120	(84)
CA1 hippocampus			120					1.6	1.2	210	(85)
Cerebellar Purkinje	1										(22)
Thalamus LD							2.6				(33)
Retinal ganglion							10 (50%)				(86)
Motoneuron	1.4						10 (approx. 5%)				(21)
Sensory neuron	3					5 (11%)	5 (19%)	2			(38, 50)
NG108-15	1 (50%)				10 (63%)						(87)
NIE-115							30 (NE)		30 (40%)		(88)
Atrial myocytes	1.2			5.7							(20)
Ventricular myocytes									10 (80%)		(89)
Aorta SMC		30						0.6	0.1	30	(39)
Azygos vein SMC	approx. 0.1										(14)
Adrenal fasciculata	1.0										(27)
Spermatocytes	5	70				0.04	0.4				(61)
Pituitary GH3			51				50			131	(90)
Thyroid hMTC	2.7	10				4.7	10 (NE)				(29)
Skeletal muscle	0.7										(25)
Ca _v 3.1	0.4 – 1.2										(18, 19, 30)
Ca _v 3.2	1.1 – 1.2	1 (17%)		31	10 (44%)						(18, 20, 67)
Ca _v 3.3	1.5 – 2.3										(18, 19)

All concentrations reported are micromolar and represent the IC₅₀ values determined from dose-response measurements. Studies where only a single concentration was studied are noted by giving the concentration and the percent inhibition observed or NE if no significant effect was observed. The charge carrier used in each study is as follows (in mM): (reference 32) 5 Ca²⁺, (84) 10 Ca²⁺, (85) 10 Ca²⁺, (22) 5 Ba²⁺, (33) 2 Ca²⁺, (86) 10 Ca²⁺, (21) 5 Ba²⁺, (38) 5 Ba²⁺, (50) 10 Ba²⁺, (87) 10 Ba²⁺, (88) 20 Ba²⁺, (20) 1.8 Ca²⁺, (89) 5.4 Ca²⁺, (39) 20 Ca²⁺, (14) 20 Ba²⁺, (27) 10 Ca²⁺, (61) 10 Ca²⁺, (90) 10 Ca²⁺, (29) 30 Ba²⁺, (25) 10 Ba²⁺, (18) 10 Ba²⁺, (19) 2 Ca²⁺, (30) 20 Ba²⁺, (67) 15 Ba²⁺.

Many studies indicate that mibefradil is also capable of blocking various other ion channels at micromolar concentrations. It can also block Ca^{2+} - and volume activated Cl^- channels of calf endothelial cells with IC_{50} s of approximately $5\ \mu\text{M}$, while in the same preparation, the inwardly rectifying K^+ channel was not affected at concentrations up to $30\ \mu\text{M}$ (24). In skeletal myoblasts, mibefradil blocked three voltage-gated K^+ currents, including an inward rectifier, a delayed rectifier, and a human *ether-a-go-go* with a respective IC_{50} of 5.6, 0.3 and $0.7\ \mu\text{M}$ (25). The observation that mibefradil also blocks outward K^+ currents with similar potency as T-type currents was corroborated in adrenal zona fasciculata cells, where the ATP-activated K^+ current expressed was inhibited by mibefradil with an IC_{50} of $0.5\ \mu\text{M}$ (26), a concentration twofold lower than that required to inhibit T-type Ca^{2+} currents under similar conditions (27). The effect of mibefradil on K^+ currents suggest that, in the case of cardiac cells, the action potential duration, resting membrane potential or even rhythmic activity could be altered by this drug. As a result, ventricular arrhythmias may occur, and this could explain in part the cardiovascular toxicity of this drug when used in combination with antihistamines. Finally, binding experiments showed that nanomolar concentrations of mibefradil can compete with [^3H]-WIN17317-3 binding to Na^+ channels of guinea pig synaptic membranes; this observation was confirmed with electrophysiological experiments using GH3 cells, whose Na^+ currents were inhibited by mibefradil with an IC_{50} around $1\ \mu\text{M}$ (28).

Interestingly, the apparent potency of mibefradil depends on both the charge carrier used to record the currents and its concentration. Its sensitivity is lower in Ba^{2+} than in Ca^{2+} (29) and lower at higher divalent concentrations. For example, its potency decreases 4.5- to 9-fold by increasing the charge carrier concentration from 2 to $10\ \text{mM}$ (18). These results suggest that mibefradil could be competing with permeant ions for a binding site in the channel. These observations are particularly relevant since most studies of mibefradil's block have used $10\ \text{mM}$ charge carrier and thus have underestimated its potency (Table 1).

Studies on the mechanism of mibefradil block of T-type currents have yielded variable results. Early studies using a thyroid cancer cell line (hMTC, or TT cells) found little evidence for state-dependent block (29). Recent studies using rat cerebellar Purkinje neurons (22), pig atrial myocytes (20) or bovine adrenocortical cells (27) have conclusively demonstrated that mibefradil clearly shows higher affinity (5- to 20-fold) for partially inactivated states of the channel. This result has been confirmed using the cloned $\alpha 1\text{G}$ and $\alpha 1\text{H}$ channels (18, 30). Mibefradil was found to be fivefold more potent at potentials where half the channels are inactivated (18). A possible reason this effect was not observed in hMTC cells was that the measured currents were con-

taminated by other Ca^{2+} channels (29). To allow comparisons between studies, the values reported in Table 1 represent block of channels measured in supra-physiological concentrations of charge carrier at well-hyperpolarized potentials. It should be noted that at physiological concentrations of Ca^{2+} and membrane potentials, mibefradil blocks $\alpha 1\text{H}$ with an apparent IC_{50} of $70\ \text{nM}$ (18), a value that is well within the range of clinically relevant concentrations. Since mibefradil also blocks L-type channels in a voltage-sensitive manner, it is difficult to discern whether T-type channel block is relevant to its anti-hypertensive effect.

Interestingly, the corollary has also been suggested: a block of T-type channels might contribute to the anti-hypertensive activity of dihydropyridines such as felodipine and to the antiarrhythmic activity of amiodarone and bepridil (31). Akaike and coworkers have extensively studied the sensitivity of neuronal T-type currents to calcium channel blockers (Table 1). The diphenylpiperazine flunarizine was the most potent. In fact, in hypothalamic neurons, they found that flunarizine was *more* potent at blocking T- than L-type currents, while nimodipine and diltiazem were equipotent (32). These studies demonstrated that many dihydropyridines blocked neuronal T-type currents at micromolar concentrations, with nicardipine being the most potent. Since early studies using $0.1 - 1\ \mu\text{M}$ dihydropyridines had shown selective block of L-type channels with little block of T-type channels, these authors concluded that there was a sub-set of dihydropyridine-sensitive T-type channels. This hypothesis was supported in studies on the changes that occur in thalamic T-type currents during development (33). Similarly, felodipine displayed an apparent affinity for inactivated T-type channels of atrial myocytes of $13\ \text{nM}$, but only $700\ \text{nM}$ for those of pituitary GH₃ cells (31).

Clearly the dihydropyridine structure-activity relationships of T- and L-type channel are different. This is most clearly demonstrated by the stereoisomers of Bay K8644: T-type channels are weakly blocked by micromolar concentrations of both (34), while for L-type channels, sub-micromolar concentrations of the (+) isomer effectively block the current, while the (–) isomer is an *agonist*, similar to the racemic mixture (35). Stimulation of LVA currents by Bay K8644 are very difficult to interpret directly because L-type channel gating is shifted to more negative potentials. In contrast, the stereoselectivity and potency of nifedipine was similar for both L- and T-type channels; the racemic mixture blocked T-type currents in guinea pig atrial myocytes with an IC_{50} of $0.18\ \mu\text{M}$ (36).

Although the binding site for dihydropyridines is different between L- and T-type channels, the mechanism of block appears similar. Dihydropyridines appear to stabilize inactivated states of both channels, causing a negative shift in the steady-state availability curve (31, 37–39).

Flunarizine also blocks T-type channels in a voltage-dependent manner, while diltiazem and verapamil do not (39).

Antiepileptics

Epilepsy is a disorder of the nervous system characterized by neuronal hyperexcitability. There are many forms of epilepsy, and they have been broadly classified into either partial or generalized seizures. The drugs used to treat the symptoms of these disorders differ. Antiseizure drugs are thought to tip the balance between neuronal excitation and inhibition by two mechanisms: 1) by blocking Na^+ or Ca^{2+} channels, and hence limiting the sustained repetitive firing of neurons, or 2) by enhancing the activity of inhibitory neurotransmitters, notably gamma-aminobutyric acid (GABA). Despite the fact that few drugs have been systematically tested on both Na^+ and Ca^{2+} channels, a dogma has arisen that Na^+ channel blockers are useful in partial seizures, while T-type channel blockers are only useful in generalized seizures.

Table 2 provides numerous examples of blocking T-type channels by “ Na^+ channel blockers.” Perhaps the best studied is phenytoin, which clearly blocks both channels at therapeutic concentrations (40). The mechanisms of block are also similar, with higher affinity for inactivated states of the channel. Studies using cloned T-type channels indicated that $\text{Ca}_v3.2$ was the most sensitive, although the block was variable even in a cloned cell, suggesting that additional factors may be important for block (41).

Ethosuximide is considered the prototypical absence seizure drug that works by inhibition of T-type channels. This hypothesis was based on the finding that ethosuximide could partially block T-type currents in thalamic neurons at therapeutically relevant concentrations (42). Support for this hypothesis came from studies with related analogs (43). For one, T-type current block was also observed at therapeutically relevant concentrations of methyl-phenylsuccinimide (MPS), the active metabolite of methsuximide. MPS differs from ethosuximide by having a phenyl substituent at the 4 position rather than an ethyl group (Fig. 2). Second, no block was observed using the convulsant analog, tetra-methyl-succinimide. The sensitivity of T-type channels to MPS has been confirmed in many other

Fig. 2. Antiepileptics shown to block T-type calcium current.

Table 2. Antiepileptics shown to block T-type calcium currents

	Phenytoin	Ethosuximide	MPS	Zonisamide	Valproate	Phenobarbital	Reference
	(μM)	(mM)	(mM)	(μM)	(mM)	(mM)	
DRG	8 (max 58%)	24	0.14 (max 42%)		0.3 (max 17%)	1.7	(41, 50)
DRG		0.007					(44)
Nodose ganglion					1 (16%)		(91)
NB1	30 (50%)			50 (38%)			(92)
Cerebral cortex				500 (60%)			(93)
Thalamus VB	100 (33%)	0.2 (max 40%)	1.1		1 (NE)		(42)
Thalamus VB			3 (52%)				(94)
Thalamus nRT			3 (53%)				(94)
Hippocampus CA1	100 (43%)						(57)
GH3	100 (36%)	2.5 (10%)					(90)
$\text{Ca}_v3.1$	140	14	1.7		3 (4%)	1.5	(41)
$\text{Ca}_v3.2$	8 (max 45%)	22	2.3		1 (9%)		(41)

Some compounds did not totally block the T-type current at the maximum dose tested. In such cases the values in the table represent the apparent IC_{50} with the maximum (max) block obtained in parentheses. Studies where only a single concentration was studied are noted by giving the concentration and the percent inhibition observed or NE if no significant effect was observed. The charge carrier used in each study is as follows (in mM): (reference 41) 2 Ca^{2+} , (50) 10 Ba^{2+} , (44) 1.8 Ca^{2+} , (91) 5 Ca^{2+} , (92) 51 Ba^{2+} , (93) 7 Ca^{2+} , (42) 3 Ca^{2+} , (94) 3 Ca^{2+} , (57) 10 Ca^{2+} , (90) 10 Ca^{2+} . Other abbreviations include: MPS, methylphenylsuccinimide; DRG, dorsal root ganglion; NB-1, neuroblastoma; nRT, reticular nucleus; and VB, ventrobasal.

systems, including the cloned channels (Table 2). With one notable exception (44), most studies have failed to confirm block of T-type currents at therapeutically relevant concentrations, leading to the suggestion that block of other ionic channels may be more relevant (45).

Some antiepileptics are characterized by hydantoin and imide molecular frameworks (Fig. 2). Hydantoins include phenytoin and phenobarbital and consist of a carbonyl-amine-carbonyl-amine moiety. Imides such as MPS and ethosuximide have the alternating carbonyl-amine functionality but without the additional carbonyl. It is reasonable to think that the T-channel protein would exhibit differential sensitivity to isomers of an antagonist. Such is the case with EMTBL, a cyclic thioester, where α -EMTBL exhibits blocking activity 5 times that of the β stereoisomer in rat dorsal root ganglion (DRG) (46). Chlordiazepoxide, a benzodiazepine tranquilizer that also has anti-convulsant effects, blocks both LVA and HVA channels with IC_{50} s of approximately 0.3 mM (47). Valproic acid is structurally the simplest of the antiepileptics listed in Fig. 2. Only partial block by valproic acid has been observed (Table 2). Zonisamide, a relatively new anti-epileptic, contains both a sulfonamide and oxazole functionality. It too was only capable of partial block. Based on a limited amount of experimental evidence, T-type channel block is thought to underlie the mechanism of action of both valproic acid and zonisamide.

Anesthetics

Although the precise mechanism of action of anesthetics is unknown, many studies have demonstrated that they are capable of blocking ion channels. Many general anesthetics appear to potentiate chloride currents through ligand-gated GABA and glycine channels. A newly described mechanism for inhalation anesthetics is that they hyperpolarize

neurons by potentiating the activity of leak K^+ currents carried by the two pore domain channels such as TASK-1 (48). Table 3 lists the block of T-type calcium channels by various types of anesthetics, and their structures are shown in Fig. 3.

In contrast to the tissue variability noted above, there is general agreement between studies on the potency of various inhalation anesthetics (Table 3), although decreased sensitivity of cardiac T-type currents has been noted (49). Both isoflurane and halothane block T-type currents at therapeutically relevant concentrations of anesthetics (50). Block of high voltage-activated currents by halothane occurs at similar millimolar concentrations (51, 52).

Steroid analogs have been developed that are neuroactive, including some such as alphaxalone that are anesthetic (53). New compounds have been synthesized that do not interact with GABA or Na^+ channels, such as ACN and ECN (54). It is interesting to note that of the stereoisomers of ACN and ECN, it is the (+) enantiomer of both that was most active. This suggests that the alcohol and cyano functionalities are interchangeable, since the activities (+)-ECN and (+)-ACN are essentially the same despite a 'swap' of the two functional groups. T-type currents of rat DRG neurons were partially blocked by (+)-ECN (40% maximal inhibition; IC_{50} , 0.3 μ M), while (–)-ECN block occurred at 30-fold higher concentrations (54). It also produced partial block of HVA currents (approximately 30% maximal inhibition; IC_{50} , 9 μ M). Among HVA currents, (+)-ACN appears to be somewhat selective for members of the Ca_v2 family (55).

Octanol (20 μ M), an aliphatic alcohol, was reported to block LVA currents totally from inferior olivary neurons (56). Subsequent studies required much higher concentrations for block (Table 3). Studies on hippocampal CA1 pyramidal neurons indicated that octanol is non-selective,

Table 3. Anesthetics and barbiturates shown to inhibit T-type calcium currents

	Isoflurane	Enflurane	Halothane	Pentobarbital	Thiopental	Etomidate	Propofol	Ketamine	Octanol	Reference
	(mM)	(mM)	(mM)	(mM)	(mM)	(mM)	(μ M)	(mM)	(mM)	
DRG (neonatal rat)			0.1							(52)
DRG (rat)	0.3	1.2 (56%)	0.6	0.3		0.2	13	2.5	0.12	(41, 49, 50)
Hippocampus	1 (75%)								0.3 (53%)	(57, 95)
Ventricular myocytes	1.2 (20%)		1.4 (20%)							(49)
Adrenal glomerulosa	0.7 (47%)	1.2 (56%)	0.7 (24%)							(49)
GH3			1.3	1					0.24	(51, 90)
Thyroid carcinoma	0.7 (33%)	1.2 (46%)	0.7 (24%)							(49, 96)
$Ca_v3.1$	0.3			0.3	0.3	0.16	20	1.2	0.16	(41)
$Ca_v3.2$				0.3			27		0.22	(41)

The values represent either the IC_{50} determined from dose-response measurements or the percent inhibition (in parentheses) by a single concentration. The charge carrier used in each study is as follows (mM): (reference 52) 10 Ca^{2+} ; (41) 2 Ca^{2+} ; (49) adrenal glomerulosa: 20 Ca^{2+} , DRG: 2 Ca^{2+} , thyroid: 10 Ca^{2+} , ventricular myocyte: 2 Ca^{2+} ; (50) 10 Ba^{2+} ; (57) 2 Ca^{2+} ; (95) 5 Ca^{2+} ; (51), 10 Ca^{2+} ; (90) 10 Ca^{2+} ; (96) 10 Ca^{2+} .

Fig. 3. Anesthetics shown to block T-type calcium current.

blocking T-, N- and L-type channels to a similar extent (57).

Antipsychotics

Antipsychotics, introduced in the 1950s, are used today in the treatment of psychotic disorders such as schizophrenia, the main phase of manic-depressive illness and other acute idiopathic psychotic illnesses (58). Anti-psychotics (neuroleptics) primarily act to block the D2 dopaminergic receptors, thereby inactivating dopamine neurotransmission in the forebrain. In addition, some neuroleptics can act on the D1 dopaminergic, 5-HT₂ serotonergic and α_2 -adrenergic receptors (59).

The antipsychotics shown in Fig. 4 are characterized by varying degrees of aromaticity, and heterocyclic, non-aliphatic amines. The core amine heterocycles are all 1,4 di-substituted. Five of the six compounds have halogens (chlorine and fluorine) on the aromatic rings located primarily at the *para* position. With the exception of clozapine, all these compounds have short (2–3) carbon aliphatic chains connecting the heterocyclic amines to the aromatic rings. The most structurally similar compounds are penfluridol, fluspirilene and pimozide. The higher sensitivity of T-type channels to penfluridol might be attributed to a decrease in steric bulk and hydrogen bonding ability of the hydroxyl at the 4 position compared to the others. Despite strikingly different structures, thioridazine, clozapine and haloperidol have comparable activity in TT cells, but are still much less active than fluspirilene or penfluridol (60).

Of the three diphenylbutylpiperidines, penfluridol was

the most effective at blocking T-type currents of human medullary thyroid cancer (TT) cells (60). In these cells, penfluridol blocked with an IC₅₀ of 224 nM. It was also approximately tenfold more selective for LVA currents over HVA currents as 500 nM penfluridol inhibited 82% of the LVA current but only 20% of the HVA. Both penfluridol and pimozide block in a state-dependent manner, consistent with a lower affinity to the resting state (60, 61). Of all the compounds tested on T-type currents, these are the only class of drugs with IC₅₀'s in the sub-micromolar range (Table 4). Unfortunately, they are also very potent blockers of K⁺ channels (26) and bind tightly to L-type channels (62).

Others

Amiloride is a potassium-sparing diuretic that acts by blocking a *non*-voltage-activated Na⁺ channel in kidney epithelial cells (ENaC). It can also block voltage-gated channels, preferentially blocking LVA currents with little block of HVA channels or voltage-activated Na⁺ channels (63). Studies using cardiac myocytes have confirmed the selectivity of amiloride for T- vs L-type channels (64, 65). Its selectivity for LVA currents has been a useful tool in a number of studies on neuronal Ca²⁺ currents (66). In contrast, most studies have not confirmed amiloride's sensitivity, requiring up to 30-fold higher concentrations (Table 5). Although this discrepancy might be explained by differential sensitivity of the T-type channel subtypes (67, 68), it does not explain discrepancies between studies on the same cell type. For example, using mouse spermato-

Fig. 4. Antipsychotics shown to inhibit T-type calcium channel activity.

Table 4. Antipsychotics shown to inhibit T-type calcium channel activity

	Penfluridol	Fluspirilene	Clozapine	Haloperidol	Thioridazine	Pimozide	Reference
Pituitary (rat)-GH4C1	1 (45%)	2 (64%)					(97)
Thyroid carcinoma (rat)	0.2						(60)
Thyroid carcinoma (human)	0.1 (70%)	1 (90%)	10	5 (31%)	10 (25%)		(60)
Spermatocytes (mouse)						0.5	(61)

All concentrations reported are micromolar and represent the IC_{50} values determined from dose-response measurements. Studies where only a single concentration was studied are noted by giving the concentration and the percent inhibition observed. The charge carrier used in each study is as follows (mM): (reference 97) 5 Ca^{2+} , (60) 10 Ca^{2+} , (61) 10 Ca^{2+} .

genic cells, Santi and co-workers (69) found that 0.5 mM amiloride only blocked 62% of the T-type current, while Arnoult et al. found that roughly half this concentration produced half-maximal block, reporting an IC_{50} of 0.24 mM (17). In addition to blocking ENaC channels, the usefulness of millimolar concentrations of amiloride is further limited by its block of transporters, such as the Na^+/H^+ and Na^+/Ca^{2+} transporters (70).

It has been hypothesized that blockade of T-type channels may provide a neuroprotective effect after ischemia (71, 72). To this end, a number of dimethylphenyl-piperazines (e.g., U-92032 (73)) and arylpiperidine analogs (e.g., SUN N5030 (72)) have been evaluated (Fig. 5). Although analogs have been described that are selective for LVA over HVA channels, they block voltage-gated Na^+ channels at similar concentrations. Similarly, the lamotrigine analog sipatrigine is a neuroprotective agent, is capable of blocking T-type channels, and can block Na^+ channels (74).

Tetrandrine, a plant alkaloid isolated from the root of *Stephania tetrandra*, was equally effective at blocking T-channels in adrenal glomerulosa cells, Y_1 adrenocortical tumor cells and bullfrog cardiomyocytes at approximately 10 μ M (Table 5). It also blocks L-type channels at similar concentrations (75).

In contrast to their potent effects on HVA channels, a

selective peptide toxin for LVA channels has yet to be isolated from either spider or snail toxins. A scorpion toxin was isolated that appeared to be selective for LVA channels, since 350 nM could block currents through cloned T-type channels with no effect on the cloned HVA channels $Ca_v1.2$, $Ca_v2.1$, $Ca_v2.2$ and $Ca_v2.3$ (76). Unfortunately its usefulness is limited by its ability to modify gating of Na^+ channels.

Conclusions

Because T-type calcium currents have been found in a variety of tissue and cell types, many physiological and pathophysiological functions for the channel have been proposed. T-type channels are most abundant in neurons, especially in medium-sized neurons from sensory ganglia (77). T-type currents have also been recorded from smooth muscle myocytes, pancreatic β cells, adrenocortical cells, osteoblasts, fibroblasts and glial cells (13). Physiological roles for the T-type channel include smooth muscle contraction, hormone (but not neurotransmitter) secretion and regulation of neuronal excitability, where they mediate rebound burst firing (13, 78). Increased T-type channel expression has been observed in proliferating and hypertrophic myocytes, leading to the hypothesis that they may also be involved in cell cycle progression (reviewed in

Table 5. Other compounds shown to block T-type calcium channels

	Amiloride	U-92032	Tetrandrine	Reference
	mM	μ M	μ M	
DRG (chick)	0.03			(63)
DRG (rat)	0.076			(50)
Motoneuron	1 (74%)			(21)
Neuroblastoma, N18	0.03			(63)
Neuroblastoma, N1E-115		6 (50%)	2.5 (max 70%)	(73, 88)
Neuroblastoma, IMR-32	0.5 (58%)			(98)
Thalamus nRT	0.5 (41%)			(94)
Thalamus VB	0.5 (38%)			(94)
Hippocampus CA1	0.3 (43%)	0.5		(57, 99)
Atrial myocytes		1		(100)
Ventricular myocytes	0.23		10 (57%)	(64, 75)
Cardiac Purkinje	0.25 (50%)			(65)
GH3	1.55			(90)
Spermatocytes	0.24			(61)
Ca _v 3.2	0.17			(67)

The charge carrier used in each study is as follows (in mM): (reference 63) 5 Ca²⁺, (50) 10 Ba²⁺, (21) 5 Ba²⁺, (73) 50 Ba²⁺, (88) 20 Ba²⁺, (98) 10 Ca²⁺, (94) 3 Ca²⁺, (57) 10 Ca²⁺, (99) 2 Ca²⁺, (100) 5 Ca²⁺, (64) 5.4 Ca²⁺, (75) 1.8 Ca²⁺, (65) 5 Ca²⁺, (90) 10 Ca²⁺, (61) 10 Ca²⁺, (67) 15 Ba²⁺. Abbreviations: DRG, dorsal root ganglion; N1E-115, mouse neuroblastoma; nRT, reticular nucleus; VB, ventrobasal.

Fig. 5. A variety of structurally diverse compounds that block T-type calcium current.

ref. 13). Although to date there are no highly selective T-type channel blockers, studies using a variety of compounds that all have activity against these channels have led to the conclusion that selective blockers might be useful in regulating proliferation, blood pressure and abnormal neuronal firing. T-type channels may play a central role in thalamic dysrhythmias and therefore blockers may be useful not only against epilepsy but also a wide spectrum of neurological disorders (79). The clinical observation that high doses of anti-epileptics are analgesic, coupled with the observation that sensory neurons contain large T-type currents, leads to the speculation that a T-type channel drug

may be useful in the treatment of neuropathic pain (80). It is important to note that in many neurons, T-type channels may serve as pacemaker currents, depolarizing the membrane to a level where Na⁺ channels may fire. In these cases, there is a “pharmacological amplification” (81) of T-type channel inhibition such that even 10% block may lead to a pronounced effect on neuronal firing (82). It should also be noted that selectivity for T-type channels may be conferred by a drug’s preference for inactivated channels. This may be particularly true in thalamic dysrhythmias since T-type channels are partially inactivated in states of wakefulness (83).

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