



Universiteit
Leiden
The Netherlands

Convergent evolution of toxin resistance in animals

Thiel, J. van; Khan, M.A.; Wouters, R.M.; Harris, R.J.; Casewell, N.R.; Fry, B.G.; ... ;
Richardson, M.K.

Citation

Thiel, J. van, Khan, M. A., Wouters, R. M., Harris, R. J., Casewell, N. R., Fry, B. G., ...
Richardson, M. K. (2022). Convergent evolution of toxin resistance in animals. *Biological
Reviews*, 97(5), 1823-1843. doi:10.1111/brv.12865



Version: Publisher's Version

License: [Creative Commons CC BY-NC 4.0 license](#)

Downloaded from: <https://hdl.handle.net/1887/3563315>

Note: To cite this publication please use the final published version (if applicable).

Convergent evolution of toxin resistance in animals

Jory van Thiel^{1,*} , Muzaffar A. Khan¹, Roel M. Wouters¹, Richard J. Harris², Nicholas R. Casewell³, Bryan G. Fry², R. Manjunatha Kini^{4,5,6}, Stephen P. Mackessy⁷, Freek J. Vonk^{8,9}, Wolfgang Wüster¹⁰ and Michael K. Richardson^{1,*} 

¹*Institute of Biology Leiden, Leiden University, Sylviusweg 72, 2333 BE Leiden, The Netherlands*

²*Venom Evolution Lab, School of Biological Sciences, University of Queensland, St Lucia, 4072, Australia*

³*Centre for Snakebite Research & Interventions, Liverpool School of Tropical Medicine, Pembroke Place, Liverpool L3 5QA, U.K.*

⁴*Department of Biological Sciences, National University of Singapore, Singapore, 117558, Singapore*

⁵*Department of Pharmacology, Yong Loo Lin School of Medicine, National University of Singapore, Singapore, 117600, Singapore*

⁶*Department of Biochemistry, Medical College of Virginia, Virginia Commonwealth University, Richmond, VA, 23298, U.S.A.*

⁷*School of Biological Sciences, University of Northern Colorado, Greeley, CO, 80639-0017, U.S.A.*

⁸*Naturalis Biodiversity Center, Darwinweg 2, 2333 CR Leiden, The Netherlands*

⁹*Amsterdam Institute of Molecular and Life Sciences, Division of BioAnalytical Chemistry, Department of Chemistry and Pharmaceutical Sciences, Vrije Universiteit Amsterdam, De Boelelaan 1085, 1081HV Amsterdam, The Netherlands*

¹⁰*Molecular Ecology and Fisheries Genetics Laboratory, School of Natural Sciences, Bangor University, Bangor, LL57 2UW, U.K.*

ABSTRACT

Convergence is the phenomenon whereby similar phenotypes evolve independently in different lineages. One example is resistance to toxins in animals. Toxins have evolved many times throughout the tree of life. They disrupt molecular and physiological pathways in target species, thereby incapacitating prey or deterring a predator. In response, molecular resistance has evolved in many species exposed to toxins to counteract their harmful effects. Here, we review current knowledge on the convergence of toxin resistance using examples from a wide range of toxin families. We explore the evolutionary processes and molecular adaptations driving toxin resistance. However, resistance adaptations may carry a fitness cost if they disrupt the normal physiology of the resistant animal. Therefore, there is a trade-off between maintaining a functional molecular target and reducing toxin susceptibility. There are relatively few solutions that satisfy this trade-off. As a result, we see a small set of molecular adaptations appearing repeatedly in diverse animal lineages, a phenomenon that is consistent with models of deterministic evolution. Convergence may also explain what has been called ‘autoresistance’. This is often thought to have evolved for self-protection, but we argue instead that it may be a consequence of poisonous animals feeding on toxic prey. Toxin resistance provides a unique and compelling model system for studying the interplay between trophic interactions, selection pressures and the molecular mechanisms underlying evolutionary novelties.

Key words: convergent evolution, toxin resistance, molecular adaptation, functional constraint, deterministic evolution, co-evolutionary arms races.

CONTENTS

I Introduction	1824
II Convergent mechanisms of resistance	1825

* Authors for correspondence (Tel: +31 71 527 5215; E-mail: joryvthiel@gmail.com); (Tel: +31 71 527 5215; E-mail: m.k.richardson@biology.leidenuniv.nl)

Jory van Thiel and Muzaffar A. Khan contributed equally to this work.

(1) Snake venom metalloproteinases	1825
(2) Snake venom phospholipases A ₂	1826
(3) Snake venom C-type lectins	1827
(4) Snake venom three-finger toxins	1827
(5) Pain-inducing scorpion toxins	1830
(6) Guanidinium toxins	1830
(7) Batrachotoxins	1834
(8) Cardiac glycosides	1834
(9) Epibatidine	1835
III Evolutionary implications of toxin resistance	1835
(1) When does toxin resistance evolve?	1835
(2) Competing selection pressures and convergent evolution	1836
(3) Origins of autoresistance in poisonous animals	1838
IV Conclusions	1838
V Acknowledgements	1838
VI. References	1839
VII. Supporting information	1843

I INTRODUCTION

Convergent evolution is the independent emergence of similar traits across different lineages (Storz, 2016). Toxins are key innovations that have evolved throughout the tree of life (Yamaguchi, Park & Inouye, 2011; Casewell *et al.*, 2013). They act on specific molecular targets (e.g. receptors, ion-channels, enzymes, and plasma membranes), causing a range of pathophysiological disruptions throughout the cardiovascular, circulatory and nervous systems (Fry *et al.*, 2009; Casewell *et al.*, 2013). Venom is a mixture of proteinaceous toxins exploited for a variety of functions, including prey capture and defence, ultimately resulting in severe pain, incapacitation or death. By definition, venoms are typically injected into a target system *via* a mechanical wound caused for example by fangs (e.g. snakes, centipedes and spiders), spines (e.g. fish), nematocysts (e.g. jellyfish and sea anemones) or stingers (bees, wasps and other arthropods). Poisons on the other hand tend to consist of small-molecule toxins (e.g. low-molecular-weight alkaloid or steroidal-based compounds) that are almost exclusively utilised to deter predators – often by causing rapid pain or paralysis upon contact or ingestion (Duran-Riveroll & Cembella, 2017; Botelho *et al.*, 2019).

Therefore, toxins can be considered ecologically functional traits that mediate antagonistic interactions between predator and prey, driven by natural selection. To counteract the deleterious effects of these toxins, some animals have evolved resistance. Toxin resistance is the increased ability of an animal to survive exposure to one or more toxins without being functionally affected. As a result, toxin resistance has evolved in at least three distinct ecological contexts (Fig. 1): *predator resistance*, where a predator is resistant to the toxins of its prey (Fig. 1A–C); *prey resistance*, where the prey is resistant to the toxins of a predator (Fig. 1D); or *autoresistance*, where an animal is resistant to its own toxins (Fig. 1E).

Resistance particularly evolves in molecular targets involving key regulatory processes that are under strong selection

pressures, i.e. that are crucial for the survival of an organism. There are several molecular mechanisms underlying toxin resistance [reviewed in Holding *et al.*, 2016b and Arbuckle, Rodriguez de la Vega & Casewell, 2017]. First, *target modification* is a change in the gene sequences that encode receptors or circulating proteins to which specific toxins bind, resulting in a reduction of binding affinity of the toxin towards the target (Barchan *et al.*, 1992; Geffney *et al.*, 2005; Jansa & Voss, 2011; Tarvin *et al.*, 2017; Karageorgi *et al.*, 2019). Second, *off-target repurposing* is the molecular modification of a previously non-target site that increases its toxin-binding affinity so that the physiological effect induced by the toxin is altered, and the desired effect has thereby been repurposed (Rowe *et al.*, 2013). Finally, *toxin scavenging* involves serum-based components that patrol the circulatory system and inhibit the activity of enzymatic toxins (Perez, Pichyangkul & Garcia, 1979; Biardi *et al.*, 2011; Gibbs *et al.*, 2020).

Venom systems have been proposed as models for studying processes underlying evolutionary adaptations (Zancolli & Casewell, 2020), including convergent evolution (Casewell *et al.*, 2019; Kazandjian *et al.*, 2021; Walker *et al.*, 2021). The well-defined function (e.g. ecological interactions) and the discrete genotype–phenotype association (e.g. molecular adaptations reducing the binding affinity of a certain toxin) involving toxin resistance provide a compelling model system for studying evolutionary adaptations and drivers of fundamental processes in biology. Similar toxins are found in many different animals (Casewell *et al.*, 2013; Schendel *et al.*, 2019), and therefore they are involved in many different trophic interactions (i.e. ecological interplay between species related to diet) across many animal lineages. This provides a fascinating opportunity to study the extent of convergent evolution across unrelated taxa by incorporating the evolutionary drivers stimulating molecular adaptations leading to toxin resistance.

Here, we review current knowledge on the convergent evolution of toxin resistance, with a particular emphasis on its molecular basis and evolutionary drivers. We discuss the molecular

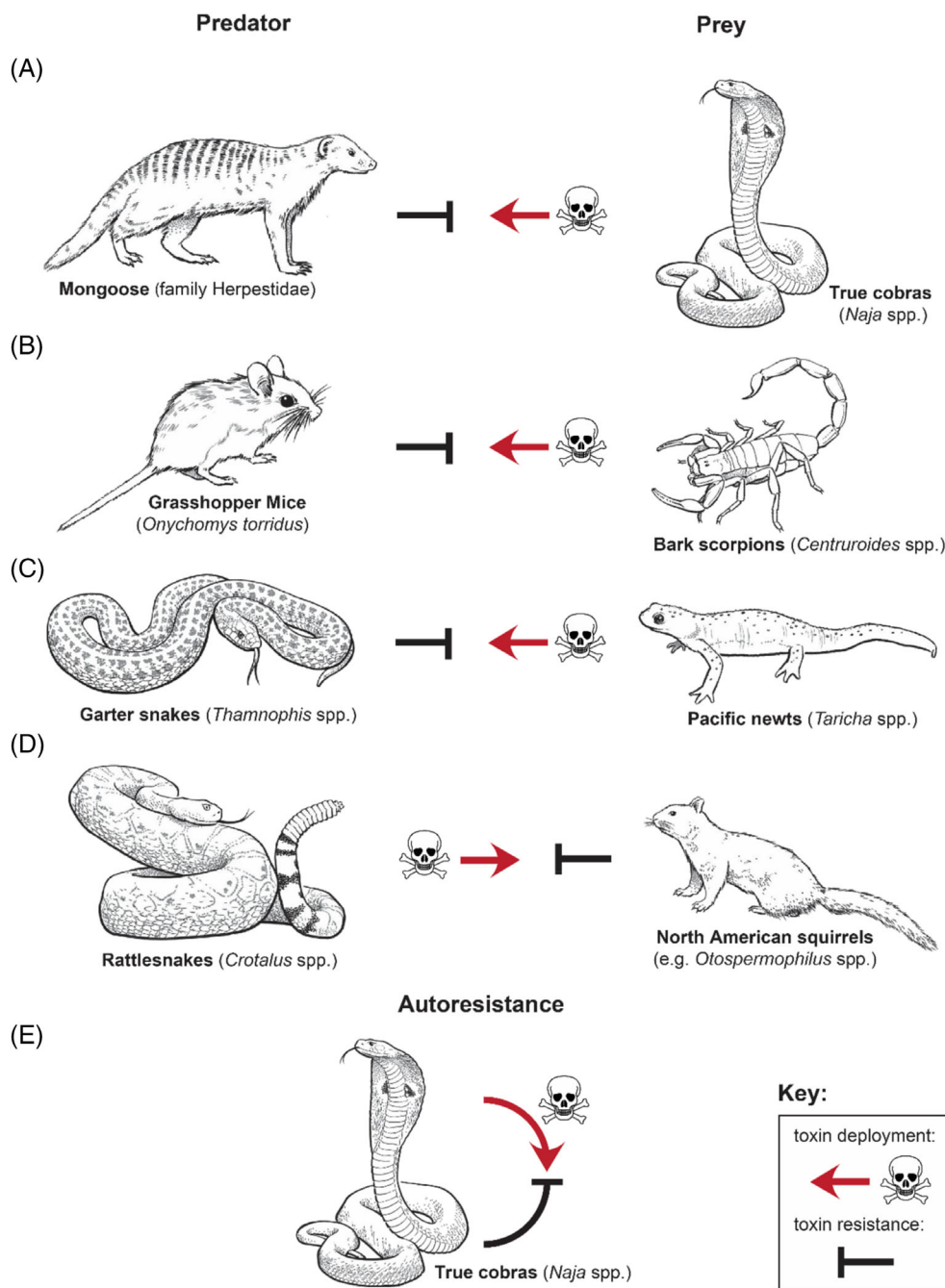


Fig. 1. Well-known examples of ecological contexts underpinning toxin resistance. (A–C) predator resistance, where a predator is resistant to the toxins of its prey. (A) The mongoose is known to predate on true cobras. (B) The grasshopper mouse preys on bark scorpions. (C) Garter snakes prey on toxic newts. (D) Prey resistance is resistance of a prey species to the toxins of a predator and is exemplified here by rattlesnakes preying on North American ground squirrels. (E) Autoresistance is where an animal is resistant to its own toxins. The example shown here is of true cobras that show resistance to cobra α -neurotoxins.

mechanisms underpinning toxin resistance across a wide range of toxin families, with diverse evolutionary drivers. We then discuss several intriguing evolutionary aspects of toxin resistance, namely: (i) the evolutionary framework underlying the appearance of toxin resistance; (ii) the role of functional constraints on molecular targets leading to convergence; and (iii) a re-examination of the evolutionary drivers of autoresistance in poisonous animals.

II CONVERGENT MECHANISMS OF RESISTANCE

(1) Snake venom metalloproteinases

Snake venom metalloproteinases (SVMPs) are zinc-dependent proteinases capable of exerting coagulopathic

and haemorrhagic effects (Ferraz *et al.*, 2019), and they are particularly abundant in viper (family Viperidae) venoms (Tasoulis & Isbister, 2017). Many animals have evolved an innate immune response mediated by SVMP inhibitors (SVMPIs). SVMPIs are acidic glycoproteins present in the circulatory system that neutralise the activity of SVMPs using a toxin-scavenging mechanism. These ‘scavenging’ inhibitors display a tight-binding reaction mechanism, mediated by the formation of non-covalent interactions and ultimately preventing the pathophysiological effects of SVMPs (Valente *et al.*, 2001). Although sharing similar functionality, SVMPIs are related to three different supergene families: (i) ficolin/opsonin p35 (Omori-Satoh, Yamakawa & Mebs, 2000); (ii) immunoglobulin (Hood, Kronenberg & Hunkapiller, 1985); or (iii) cystatin (Rawlings & Barrett, 1990). SVMPIs evolved independently across many distinct mammal (class Mammalia) and snake (suborder Serpentes) lineages.

A well-studied example of SVMP resistance can be seen in several North American squirrels (e.g. *Otospermophilus* spp., *Ictidomys* sp. and *Sciurus* sp.) that are sympatric (i.e. occurring in the same geographical area) with rattlesnakes (*Crotalus* spp.; Martinez *et al.*, 1999; Biardi *et al.*, 2011; Biardi & Coss, 2011; Pomento *et al.*, 2016). This is in contrast to squirrels that are allopatric (i.e. occurring in distinct, non-overlapping geographical areas) with rattlesnakes, which show less resistance (Poran, Coss & Benjamini, 1987; Holding, Biardi & Gibbs, 2016a; Pomento *et al.*, 2016; Gibbs *et al.*, 2020). Holding *et al.* (2016a) showed that local rattlesnake populations demonstrate higher SVMP activity in their venom; this higher activity was linked to the increased SVMPI activity in sympatric squirrels. The latter was not observed in allopatric populations. This suggests that rattlesnake venom has become adapted to maintain its selective advantage in overcoming squirrel resistance (Holding *et al.*, 2016a). This highlights the evolutionary interplay between predator and prey, resulting in convergent, geographically restricted adaptations within and across different squirrel species.

Another example is the opossum family (Didelphidae), which is sympatric with pitvipers (subfamily Crotalinae). Interestingly, they have reciprocal trophic relationships: opossums predate upon pitvipers (Oliveira & Santori, 1999; Almeida-Santos *et al.*, 2000) and pitvipers prey on opossums (Voss, 2013). Many opossum species show resistance to injected pitviper venoms (Werner & Vick, 1977; Perales *et al.*, 1994), a resistance mediated by serum SVMPIs. Evolutionary drivers underpinning resistance are likely to be species dependent; more data on trophic interactions will help address this issue (Voss, 2013).

Various other mammals, including several North American rodents (*Sigmodon* sp., *Microtus* sp. and *Neotoma* spp.), have evolved resistance to the SVMPs of sympatric pitviper species (Pichyangkul & Perez, 1981; de Wit, 1982; Garcia & Perez, 1984). Furthermore, some animals that prey on snakes, including the Indian grey mongoose (*Herpestes edwardsii*) and the European hedgehog (*Erinaceus europaeus*), also have serum SVMPIs. Most mammalian SVMPIs are related to the immunoglobulin family; however, erinacin, isolated from *E. europaeus*, is

related to the ficolin/opsonin p35 family (Mebs *et al.*, 1996; Omori-Satoh *et al.*, 2000). An overview of mammalian SVMPIs derived from the literature is provided as online supporting information in Table S1.

In addition to mammals, several snakes have also evolved serum SVMPIs that may confer resistance. In pitvipers this is likely an example of autoresistance, but in the eastern indigo snake (*Drymarchon couperi*) and Ryukyu odd-tooth snake (*Lycodon semicarinatus*) it may rather be predator resistance because these species are known to prey on sympatric pitvipers (Tomihara *et al.*, 1988; Goetz *et al.*, 2019). Another snake with serum SVMPIs is the Burmese python (*Python bivittatus*; Duan *et al.*, 2017), which likely evolved resistance in response to predation by venomous, snake-eating snakes (Jones *et al.*, 2020; Smith *et al.*, 2021). While most research has focused on serum SVMPIs, some snakes also have SVMPIs in their venom and venom glands (Munekiyō & Mackessy, 2005; Yee *et al.*, 2016; Valente *et al.*, 2018). This could be an example of autoresistance, whereby the SVMPIs protect the secretory epithelium of the venom gland and venom components from harmful effects of endogenous SVMPs (Mackessy & Baxter, 2006; Valente *et al.*, 2018). An overview of snake SVMPIs derived from the literature is provided in Table S2.

(2) Snake venom phospholipases A₂

Phospholipases A₂ (PLA₂s) are esterolytic enzymes that can cause a variety of pathological effects including myotoxicity, neurotoxicity and haemotoxicity (Manjunatha Kini, 2003; Ferraz *et al.*, 2019). They are major venom components across different snake lineages (Tasoulis & Isbister, 2017). Several animals have evolved an innate immune response mediated by PLA₂ inhibitors (PLA₂Is) that neutralise the activity of PLA₂s using a toxin-scavenging mechanism (Lizano, Domont & Perales, 2003). PLA₂Is form stable complexes, and by mimicking PLA₂-acceptors prevent binding to the cell membrane, ultimately resulting in the inhibition of the pathological effects of PLA₂s (Perales *et al.*, 1995). PLA₂Is are assigned to three structural classes (reviewed in Lizano *et al.*, 2003): PLA₂I-α (C-type lectin domain); PLA₂I-β (leucine-rich repeats domain); and PLA₂I-γ (three-finger domain). These PLA₂Is evolved convergently in snakes and opossums.

Serum-derived PLA₂Is are predominantly found in venomous snakes, including species with an abundance of PLA₂s in their venom (Tasoulis & Isbister, 2017). Interestingly, all elapid inhibitors are classified as PLA₂I-γ class, whereas viperid inhibitors are also in the PLA₂I-α and PLA₂I-β classes (see Table S3 for an overview of PLA₂Is in snakes). PLA₂I-γ of some non-venomous snakes may represent prey resistance that evolved in response to predation from venomous snakes (Thwin *et al.*, 2000; Zhong & Huang, 2016; Fortes-Dias *et al.*, 2020; Rodrigues *et al.*, 2020, 2021). PLA₂Is have also been characterised in the venom and venom gland itself, possibly representing a form of autoresistance (Mackessy & Baxter, 2006; Valente *et al.*, 2018).

The only PLA₂Is known from mammals are those of opossums. A PLA₂I has been isolated from the white-eared

opossum (*Didelphis albiventris*; Soares *et al.*, 1997). PLA₂Is are also known in the big-eared opossum (*D. aurita*). Interestingly, they show homology with the immunoglobulin supergene family. This is significant because SVMPIs isolated from other didelphids share high sequence similarities with their PLA₂I-counterpart, suggesting that similar inhibitors act on distinct snake venom toxins (Rocha *et al.*, 2002).

(3) Snake venom C-type lectins

C-type lectins (CTLs) are members of the lectin family and are predominantly found in the venom of vipers (Tasoulis & Isbister, 2017). CTLs bind to glycoprotein Ib and von Willebrand factor (vWF), thereby promoting abnormal platelet aggregation. This resistance convergently evolved within the opossum lineage, which are known to have trophic interactions with pitvipers (Oliveira & Santori, 1999; Almeida-Santos *et al.*, 2000; Voss, 2013). Several opossum species (*Didelphis* spp., *Philander* spp. and *Lutreolina* sp.) show modifications of the CTL-binding site of the vWF protein (A1 domain) under positive selection (Jansa & Voss, 2011). The modified vWF protein has substitutions that change its hydrophobicity and net charge, which is hypothesised to inhibit the binding of CTLs (Jansa & Voss, 2011). This hypothesis was supported by functional *in vitro* experiments revealing significant decreases in platelet aggregation in opossum plasma exposed to CTLs (Drabeck *et al.*, 2020). This is the first documented example of resistance-associated adaptations in a non-receptor protein targeted by venom.

(4) Snake venom three-finger toxins

Three-finger toxins (3FTX) are one of the most abundant non-enzymatic toxin families in elapid (family Elapidae) and some colubrid (family Colubridae) venoms (Tasoulis & Isbister, 2017; Modahl & Mackessy, 2019), and their principal effects are cytotoxicity and neurotoxicity. The basal activity is post-synaptic neurotoxicity through antagonistic binding to the muscle-type nicotinic acetylcholine receptor (nAChR), causing muscular paralysis and respiratory failure (Barchan *et al.*, 1995; Takacs, Wilhelmsen & Sorota, 2004). These neurotoxic effects are caused by α -neurotoxins, which primarily bind to Loop C of the ligand-binding domain (α 1-subunit) of the nAChR. Furthermore, they also show interaction with the Cys Loop, Loop F, and neighbouring delta and gamma subunits (Rahman *et al.*, 2020). Resistance to α -neurotoxins is underpinned by different molecular modifications of the ligand-binding domain of the nAChR, causing a significant reduction in their binding affinity (Barchan *et al.*, 1995; Kachalsky *et al.*, 1995; Asher *et al.*, 1998; Takacs, Wilhelmsen & Sorota, 2001; Takacs *et al.*, 2004; Dellisanti *et al.*, 2007; Rahman *et al.*, 2020; Harris & Fry, 2021; Jones *et al.*, 2021). These resistance adaptations can be generally categorised as one of four different amino acid substitutions. First, asparagine resistance is characterised by a change to asparagine, resulting in a glycosylation motif (187–189NVT or 189–191NXS/T). As a result, the *N*-

glycosylation of asparagine sterically hinders the binding of α -neurotoxins (Asher *et al.*, 1998; Takacs *et al.*, 2001, 2004; Rahman *et al.*, 2020). Secondly, arginine resistance is characterised by a replacement to arginine (187R). This change sterically hinders the binding of α -neurotoxins (Rahman *et al.*, 2020). However, since arginine is a positively charged amino acid, it has also been suggested to affect toxin binding by means of electrostatic repulsion of the positively charged α -neurotoxins (Dellisanti *et al.*, 2007; Drabeck, Dean & Jansa, 2015). Lysine resistance is characterised by a replacement to lysine (191K, 195K and/or 196K). This change to the positively charged amino acid affects the binding by means of electrostatic repulsion of α -neurotoxins (Harris & Fry, 2021). Finally, proline resistance is characterised by a replacement from proline to either a leucine or histidine (194L, 197L/H). These replacements change the structural conformation of the ligand-binding domain, and therefore affect the binding of α -neurotoxins (Kachalsky *et al.*, 1995). An overview of the key sites and mutations that confer α -neurotoxin resistance is provided in Table S4. α -Neurotoxin resistance has evolved convergently across a broad diversity of vertebrates (Fig. 2).

A classic example of α -neurotoxin resistance is seen in mongooses (family Herpestidae). For example, the Egyptian mongoose (*Herpestes ichneumon*) and the meerkat (*Suricata suricatta*) both possess a combination of asparagine resistance (187–189NVT) and proline resistance (194L; Fig. 2; Barchan *et al.*, 1992; Kachalsky *et al.*, 1995; Asher *et al.*, 1998; Khan *et al.*, 2020). Furthermore, the Egyptian mongoose also shows an additional proline replacement (197H; Fig. 2). These adaptations presumably evolved in response to predation on venomous snakes including true cobras (*Naja* spp.; Stuart, 1983; Struhsaker & McKey, 1975). However, more studies are needed to characterise the extent of trophic interactions between these mammals and snakes in the wild. Other resistant mammals include the honey badger (*Mellivora capensis*), hedgehogs (*Erinaceus europaeus* and *E. concolor*), and the wild boar (*Sus scrofa*), all of which show arginine resistance (187R; Fig. 2; Barchan *et al.*, 1995; Drabeck *et al.*, 2015; Harris & Fry, 2021). The honey badger predated upon venomous snakes, including the Cape cobra (*Naja nivea*), which has α -neurotoxin in its venom (Begg *et al.*, 2003). Wild boars and hedgehogs are also known occasionally to prey on snakes (Reeve, 1994; Tanaka & Mori, 2000; Jolley *et al.*, 2010; Wilcox, 2015). Interestingly, a recent study of primates highlighted that some groups that are sympatric with α -neurotoxic snakes had a reduced susceptibility towards α -neurotoxins of true cobras (*Naja* spp.). Members of the subfamily Homininae (*Homo*, *Pan* and *Gorilla* spp.) showed the lowest degree of susceptibility compared to other primates (Harris, Nekaris & Fry, 2021). In principle, this pattern could be explained in terms of the long history of interactions between primates and venomous snakes (Isbell, 2009; Kazandjian *et al.*, 2021).

Many birds prey on venomous snakes, including snake specialists such as the secretary bird (*Sagittarius serpentarius*), snake eagles (*Circaetus* spp.), and seriemas (family Cariamidea;

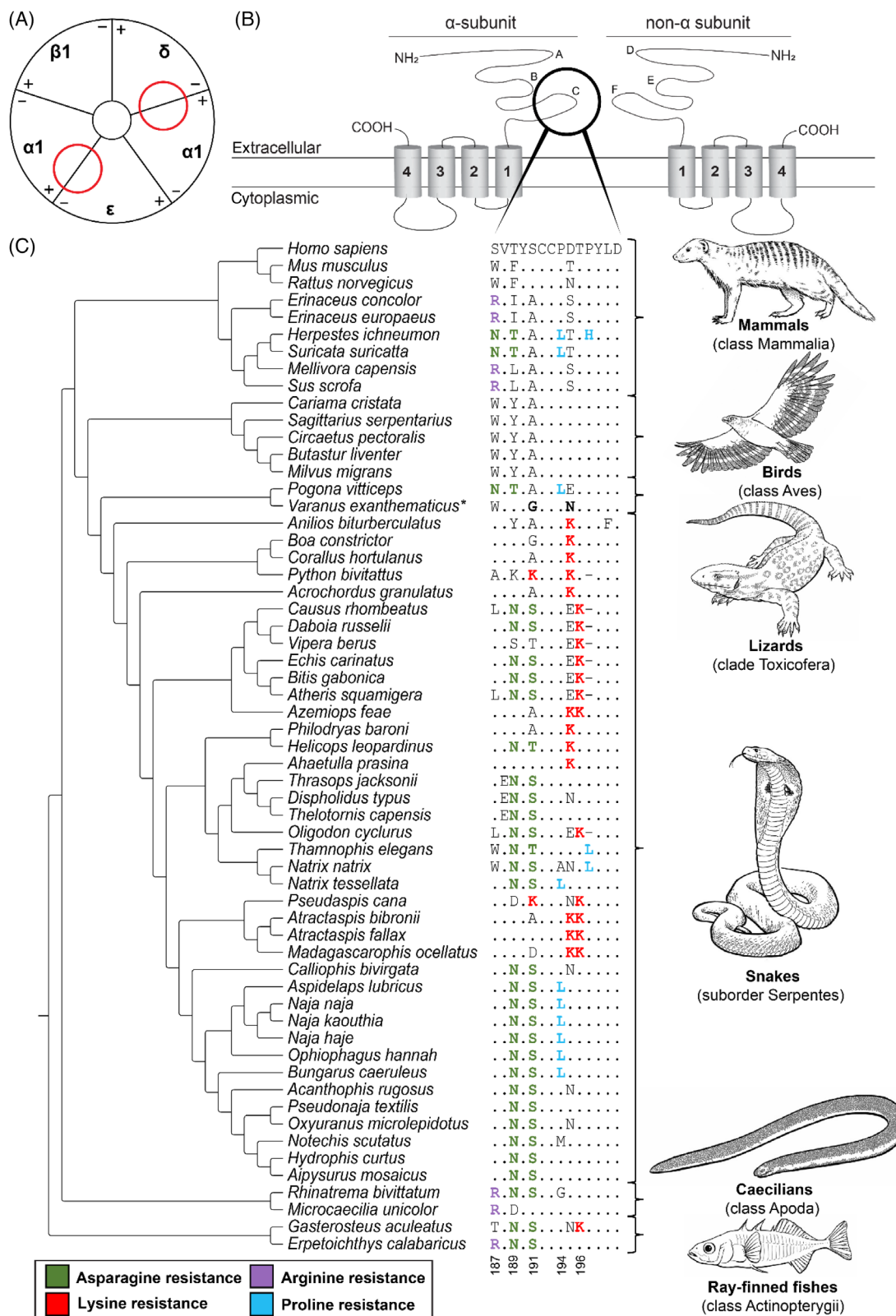


Fig. 2. Convergent evolution of α -neurotoxin resistance in animals. (A) Schematic representation (based on Kini, 2019) of the α -1 muscle-type nicotinic acetylcholine receptor (nAChR). Red circles indicate the position of the ligand-binding domain of α -neurotoxins in the nAChR. (B) Protein topology of an α -subunit and a non- α -subunit of the muscle-type nAChR. A-F indicate the loop structures at the extracellular domain in the respective subunits (Rahman *et al.*, 2020). The black circle indicates the C-loop involved in α -neurotoxin binding. (C) Sequence alignment of the α 1-nAChR ligand-binding domain. The reference amino acid sequence is from humans (*Homo sapiens*) and differences from this sequence are displayed for all other species. Substitutions associated with resistance are highlighted in coloured font. The asterisk (*) in *Varanus exanthematicus* indicates that the two substitutions shown are associated with reduced binding affinity (Jones, Harris & Fry, 2021). Tree topology based on Khan *et al.* (2020). Sequence accession numbers are provided in Table S5.

Redford & Peters, 1986; Portugal *et al.*, 2016; Mori, Vyas & Upadhyay, 2017). Birds do not show any known resistance-related modifications associated with α -neurotoxins (Fig. 2); Khan *et al.*, 2020). To explain this apparent paradox, we propose that a set of morphological exaptations and behavioural traits in snake-eating birds prevent envenomation in the first place (Fig. 3). Some examples of morphological exaptations are plumage and leg scales that may provide a physical barrier against snakebite envenomation (Lucas & Stettenheim, 1972). Additionally, bird legs mainly contain tendons and lack highly vascular tissue such as skeletal muscle; this may limit the uptake of venom if the bird is bitten. In particular, the secretary bird attacks snakes aggressively, directing kicks to the head and neck (Portugal *et al.*, 2016). Its elongated tibiotarsus and tarsometatarsus may facilitate a powerful kick (Portugal *et al.*, 2016). Birds of prey, many of which are snake-eaters, have high visual acuity and ambush hunting strategies that may minimise the risk of snakebite (Potier *et al.*, 2020). The red-legged seriema (*Cariama cristata*) uses its beak to grasp prey behind the neck and then shakes the prey violently so as to fracture its spine (Silva *et al.*, 2016). In sum, these bird-specific morphological and behavioural traits might explain why molecular adaptations conferring resistance have not

evolved among them, in contrast to other snake-eating lineages [e.g. mongoose, honey badger (Drabeck *et al.*, 2015; Khan *et al.*, 2020)].

Resistance-related mutations have been documented in lizards (clade Toxicofera) that are potentially vulnerable to predation by sympatric, neurotoxic snakes, such as the central bearded dragon (*Pogona vitticeps*; 187–189NYT, 194L) and the savannah monitor [*Varanus exanthematicus*; 191G and 195N; Fig. 2 (Khan *et al.*, 2020; Jones *et al.*, 2021)]. However, resistance has not been documented in monitor lizards (*Varanus* spp.) that have been suggested to prey on neurotoxic snakes (Jones *et al.*, 2021). Several studies hypothesised that morphological exaptations (thick, osteodermic scales) and prey-handling behaviour negated selection pressure for molecular resistance in these lizards (Jones *et al.*, 2021; Youngman, Llinas & Fry, 2021). The evolution of such strategies to avoid envenomation is comparable to what we propose for snake-eating birds (Fig. 3).

α -neurotoxin resistance is particularly widespread in snakes, which have convergently evolved asparagine resistance (189–191NXS/T), lysine resistance (191K, 195K and/or 196K) and/or, proline resistance (194L, 197L) to elapid α -neurotoxins (Fig. 2; Khan *et al.*, 2020; Harris & Fry,

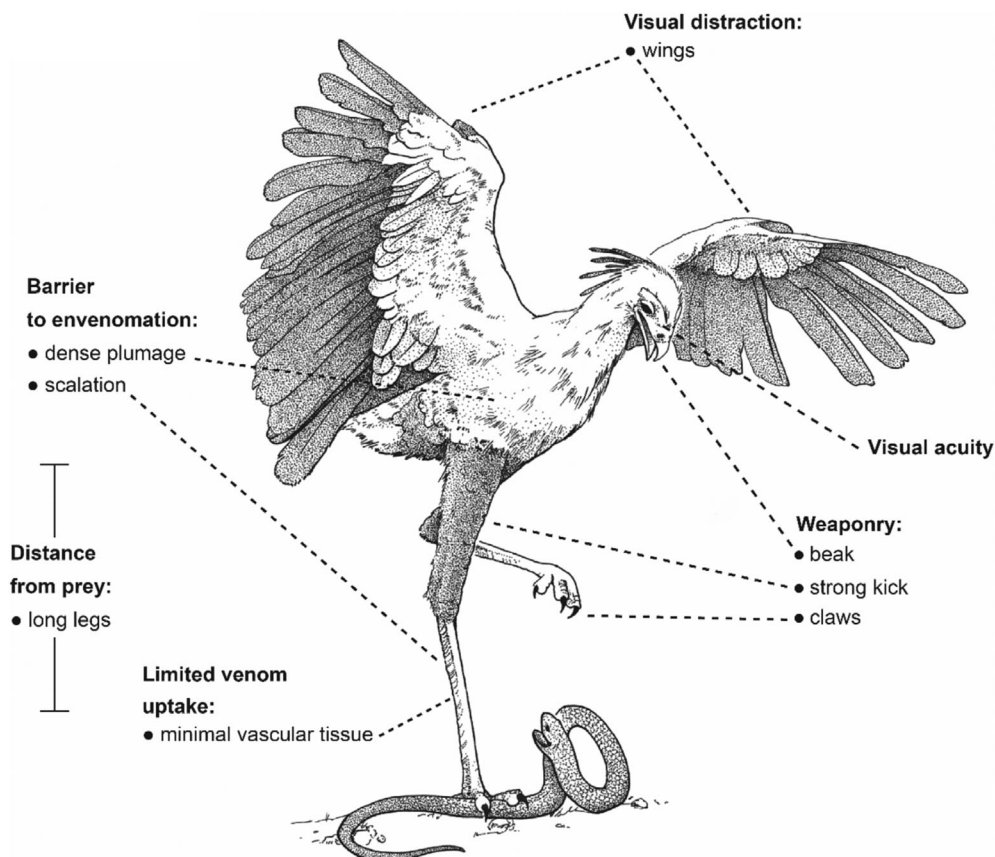


Fig. 3. Morphological exaptations and behavioural traits proposed to negate selection pressures for evolving molecular resistance in snake-eating birds such as the secretary bird (*Sagittarius serpentarius*). This figure represents multiple examples of traits unique to birds, and particularly to snake-eating birds, that might contribute to the prevention of snakebite envenomation. Drawing from an original photograph by Jason Shallcross, with permission.

2021). Resistance to these toxins in snakes is particularly interesting because – uniquely among vertebrates – snakes show all three ecological functions of resistance, namely, predator resistance, prey resistance and autoresistance. The driver of this trait is either due to selection pressure from sympatric venomous snakes or autoresistance. Elapids, including true cobras (*Naja* spp.) and the king cobra (*Ophiophagus hannah*), prey on other snakes, and this includes cannibalism (Shine *et al.*, 2007; Layloo, Smith & Maritz, 2017; Maritz, Alexander & Maritz, 2019; Jones *et al.*, 2020), and numerous species are specialised snake predators, which may have been the ancestral condition of the clade (Shine, 1991; Kgaditse, 2016). It has been suggested that predation from snake-eating elapids may have contributed to the evolution of resistance in multiple non-elapid snake lineages, an assertion that is supported by ecological observations of predation events and diet studies (Alexander & Maritz, 2010; Maritz *et al.*, 2019; Jones *et al.*, 2020). Notably, the European viper (*Vipera berus*) shows a reversal of the asparagine-resistance genotype (Fig. 2), secondary to vipers radiating into geographic areas lacking sympatric neurotoxic snakes; this may indicate that resistance mutations carry a fitness cost in species that no longer encounter α -neurotoxins (Khan *et al.*, 2020). On the other hand, this resistance may also prevent self-venomation (e.g. accidental occasions when a venomous snake bites itself) in snakes with α -neurotoxins. All elapid snakes sequenced to date share the *N*-glycosylation form of resistance to α -neurotoxins found in their own venom (Fig. 2; Khan *et al.*, 2020). Resistance to α -neurotoxins is less common in non-elapid neurotoxic snakes – but is ubiquitous within the elapids (Khan *et al.*, 2020; Harris & Fry, 2021), perhaps suggesting a strong selection pressure for the evolution of autoresistance.

Less well-documented examples have been observed in both caecilians (clade Apoda) and ray-finned fishes (class Actinopterygii). Two caecilian species have convergently evolved resistance elements: the tiny Cayenne caecilian (*Microcaecilia unicolor*; 187R) and the two-lined caecilian (*Rhinatrema bivittatum*; 189–191NYS and 187R; Fig. 2; Khan *et al.*, 2020). Both species are sympatric with caecilian-eating coral snakes (*Micrurus* spp.), which could explain this resistance (Martins & Ermelinda Oliveira, 1998). Additionally, asparagine resistance (189–191NYS) has evolved in the three-spined stickleback (*Gasterosteus aculeatus*) and the reedfish (*Erpetoichthys calabaricus*; Fig. 2; Khan *et al.*, 2020). The three-spined stickleback additionally evolved lysine resistance (196K) whereas the reedfish additionally shows arginine resistance (187R; Fig. 2). The ecological role of these modifications, if any, is unknown. A highly speculative possibility is that it could have evolved against anatoxin-a (which is an α -neurotoxin) secreted by freshwater cyanobacteria (Ar oz, Molg  & Tandeau de Marsac, 2010).

(5) Pain-inducing scorpion toxins

The venom of bark scorpions (*Centruroides* spp.) is potentially lethal, and their venom rapidly induces intense pain,

presumably to deter attackers. The pain is caused by the activation of voltage-gated Na^+ channels (Na_v 1.7), which are responsible for transmitting pain signals (nociceptive action potentials) to the central nervous system (Rowe *et al.*, 2011, 2013). The grasshopper mouse (*Onychomys torridus*) preys on arthropods including bark scorpions. It shows toxin resistance towards bark scorpion venom characterised by a diminished pain response (Rowe & Rowe, 2008; Rowe *et al.*, 2013). This resistance is underpinned by two substitutions: glutamine (859Q) and glutamic acid (862E) in the Na_v 1.8 channel (Fig. 4; Rowe *et al.*, 2013). Interestingly, these substitutions do not occur in the original targeted Na^+ channel (Na_v 1.7) but in the previously non-target Na^+ channel (Na_v 1.8), an example of off-target repurposing (Rowe *et al.*, 2013). The negatively charged glutamic acid facilitates binding of the toxin to Na_v 1.8 channels, inhibiting the transmission of pain signals by the neuron, inducing an analgesic effect (Rowe *et al.*, 2013). The pallid bat (*Antrozous pallidus*) also preys on bark scorpions (Bell, 1982; Johnston & Fenton, 2001; Lenhart, Mata-Silva & Johnson, 2010) and shows resistance to the venom of the Arizona bark scorpion (*Centruroides sculpturatus*; Hopp *et al.*, 2017). However, the unknown mechanism of resistance appears to be different; the pallid bat does not possess the resistant genotype observed in the grasshopper mouse (Fig. 4; Hopp *et al.*, 2017). This highlights that similar selection pressures do not always stimulate convergence at the molecular level.

(6) Guanidinium toxins

Guanidinium toxins, including tetrodotoxin (TTX) and saxitoxin (STX), are alkaloids that bind to the outer pores of voltage-gated Na^+ channels (Na_v) on excitable tissues, causing muscle paralysis and even death (Duran-Riveroll & Cembella, 2017). Animals that deploy these toxins for defence presumably sequester them from their diet or produce them by means of symbiotic microorganisms (Hwang *et al.*, 1989; Duran-Riveroll & Cembella, 2017). Guanidinium toxins are synthesised by several species of bacteria and then enter food webs, where they are assimilated by a wide variety of organisms (Miyazawa & Noguchi, 2001). Resistance against TTX and STX is attributed to amino acid substitutions in the α -subunit of skeletal muscle-type (Na_v 1.4) and neuronal-type (Na_v 1.6 and Na_v 1.7) voltage-gated Na^+ channels (Soong & Venkatesh, 2006). These substitutions alter TTX binding by changing the outer pore structures and/or by altering the electrostatic interaction between TTX and the pore residues (Geffeney *et al.*, 2005; Feldman *et al.*, 2012). Guanidinium toxin resistance has evolved independently in phylogenetically distinct animal lineages (Fig. 5).

Resistance against TTX has evolved convergently in at least six colubrid snake lineages (Feldman *et al.*, 2012). TTX-resistance is underpinned by numerous substitutions that decrease the binding affinity of TTX with the Na_v 1.4 channel (Fig. 5). Among these colubrid snakes, North American garter snakes (*Thamnophis* spp.) are one of the best-

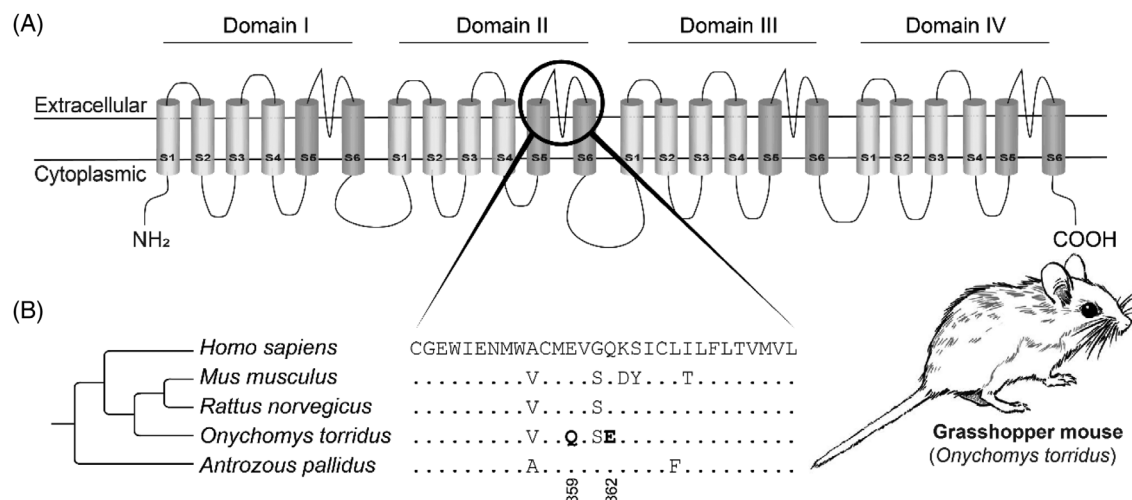


Fig. 4. Resistance against pain-inducing scorpion venom in grasshopper mouse (*Onychomys torridus*). (A) Protein topology of voltage-gated Na⁺ channel (Na_v 1.8). The black circle indicates the outer pore associated with scorpion-venom binding in the Na_v 1.8 channel. Structure based on Shen *et al.* (2017). (B) Partial sequence alignment of the outer pore of the α-subunit of domain II of the Na_v 1.8 channel. The reference amino acid sequence is from humans (*Homo sapiens*) and differences from this sequence are displayed for all other species. Substitutions associated with resistance are highlighted in bold. Tree topology based on TimeTree.org (Kumar *et al.*, 2017). For sequence accession numbers, see Table S6.

studied examples of TTX resistance (Brodie, 1990; Geffeney, Brodie & Ruben, 2002; Brodie III *et al.*, 2005; Geffeney *et al.*, 2005; Feldman *et al.*, 2009, 2010). Interestingly, resistance has evolved independently among species as well as within one species, as observed in distinct populations of the common garter snake (*T. sirtalis*; Fig. 5; Geffeney *et al.*, 2002, 2005), highlighting the ecological importance of this resistance trait. Common garter snakes also evolved TTX resistance in two additional Na_v paralogs: Na_v 1.6 and Na_v 1.7 (McGlothlin *et al.*, 2014). These paralogs are exclusively expressed in the peripheral nervous system, which is frequently exposed to TTX. By contrast, the Na_v paralogs in the central nervous system (Na_v 1.1–1.3), which are not exposed to TTX, lack any resistance modifications (McGlothlin *et al.*, 2014). The resistant Na_v paralogs (Na_v 1.6 and Na_v 1.7) were present in the common ancestor of all snakes – which initially allowed predation on toxic prey. Subsequently, this facilitated the evolution of resistance at the skeletal muscle Na_v 1.4 channel (McGlothlin *et al.*, 2016). This resistance in garter snakes is tightly linked to predation on Pacific newts (*Taricha* spp.) that deploy TTX on their skin for defence against predators (Brodie III & Brodie Jr., 1999; Williams, Brodie & Brodie, 2004; Hanifin & Gilly, 2015). Additionally, several geographically widespread colubrids (e.g. *Hebius* sp., *Rhabdophis* sp., and *Erythrolamprus* sp.) have also evolved substitutions conferring TTX-resistance (Feldman *et al.*, 2012), facilitating predation on distinct TTX-bearing amphibians (Fig. 5; Feldman *et al.*, 2012). However, the eastern hognose snake (*Heterodon platirhinos*) displays high levels of TTX resistance, but lacks these Na_v channel substitutions, suggesting a different mechanism of adaptation that remains to be elucidated (Fig. 5; Feldman *et al.*, 2016).

Another example of TTX resistance is provided by newts (family Salamandridae). One or more substitutions associated with TTX resistance evolved among these amphibians, providing them with the ability to accumulate TTX from dietary sources or (symbiotic) microorganisms and to exploit it for defensive purposes (Hanifin & Gilly, 2015; Vaelli *et al.*, 2020). Interestingly, all species show a single substitution (1532T/S) associated with TTX resistance in the Na_v 1.4 channel (Fig. 5; Hanifin & Gilly, 2015). However, some newts show three additional substitutions (1247T, 1539S, and 1540D), conferring an increased level of TTX resistance and additionally deploying higher concentrations of TTX, and they are therefore more toxic to adversaries (Fig. 5; Hanifin & Gilly, 2015). Interestingly, a recent study revealed that TTX resistance in newts is not exclusively restricted to the Na_v 1.4 channel but extends across the entire Na_v gene family, which is driven by positive selection, relaxed constraints and gene conversion events (Gendreau *et al.*, 2021).

The pufferfishes (family Tetraodontidae) are another group of animals that show TTX resistance. Different substitutions (407N/C, 1247T, and 1252P) evolved in Na_v 1.4 channels conferring resistance to TTX (Fig. 5; Yotsu-Yamashita *et al.*, 2000; Venkatesh *et al.*, 2005; Jost *et al.*, 2008). Pufferfish exploit their resistant genotype for different ecological functions, enabling them to prey on TTX-bearing species such as gastropods and echinoderms (Noguchi, Arakawa & Takatani, 2006b). Pufferfish thus accumulate high concentrations of dietary TTX in their organs, including liver, skin and ovaries (Noguchi *et al.*, 2006b). Notably, captive pufferfish kept on a TTX-free diet are not toxic, but when fed a TTX-containing diet, they started to accumulate the toxins (Noguchi, Arakawa & Takatani, 2006a; Noguchi *et al.*, 2006b). These accumulated TTXs are primarily

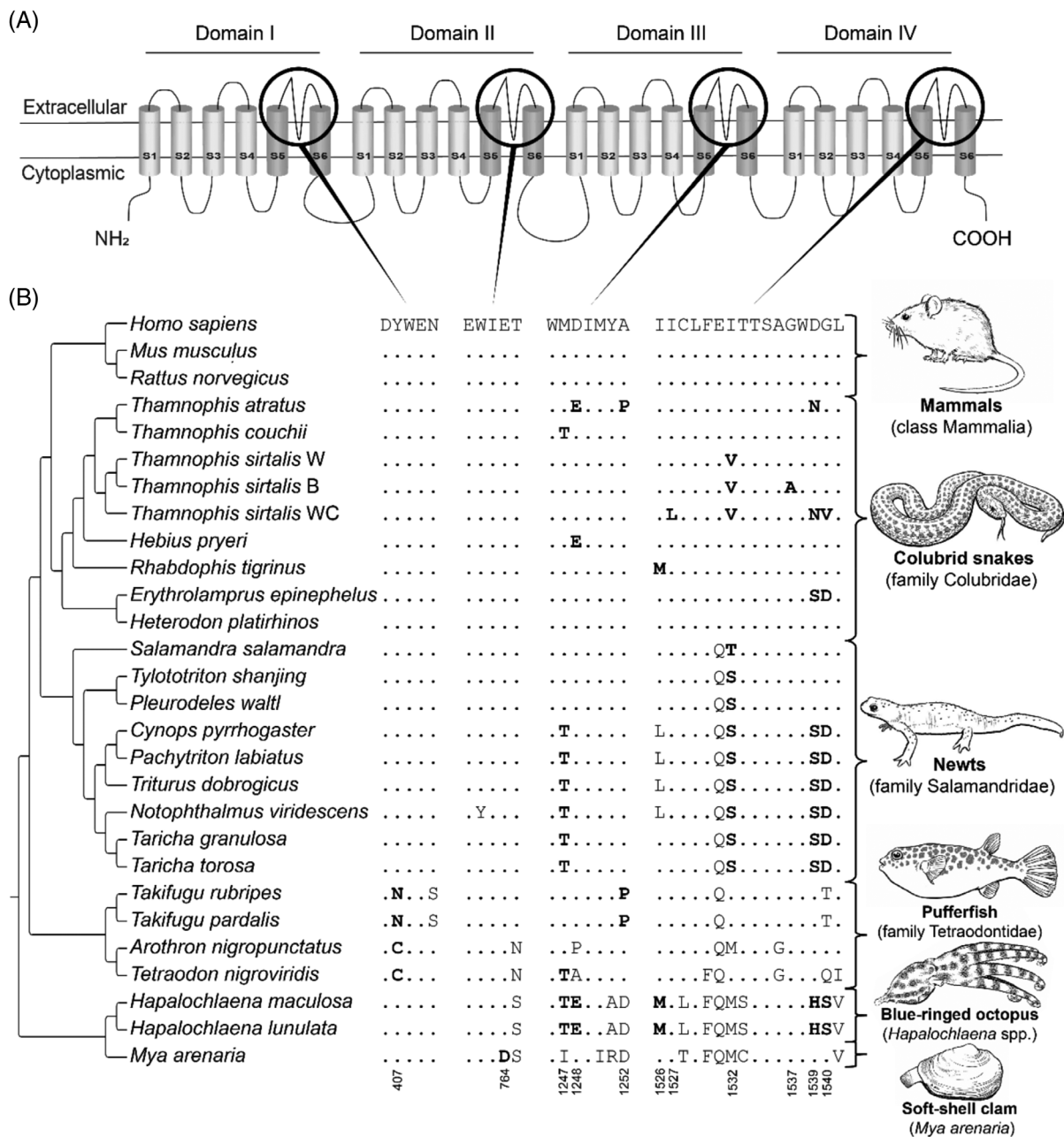


Fig. 5. Convergent evolution of guanidinium toxin resistance in animals. (A) Protein topology of the voltage-gated Na^+ channel, $\text{Na}_v 1.4$. The black circles indicate the outer pores involved in guanidinium toxin binding. Structure based on Shen *et al.* (2017). (B) Partial sequence alignments of the outer pores of the voltage-gated Na^+ channel $\text{Na}_v 1.4$. The reference amino acid sequence is from humans (*Homo sapiens*) and differences from this sequence are displayed for all other species. Substitutions associated with resistance are highlighted in bold, and their respective amino-acid positions are numbered based on $\text{Na}_v 1.4$ from *Homo sapiens*. Tree topology based on TimeTree.org (Kumar *et al.*, 2017) and taxon-specific phylogenies (Geffeney *et al.*, 2005; Feldman *et al.*, 2012; Hanifin & Gilly, 2015). Key for the *Thamnophis sirtalis* populations: B, Benton County; W, Warrenton; WC, Willow Creek. For sequence accession numbers, see Table S7.

exploited to deter predators of this otherwise innocuous fish. When threatened, pufferfish inflate their body, erecting spines and releasing TTX from the skin, thereby deterring predators (Kodama, Ogata & Sato, 1985).

TTX resistance has also evolved in some invertebrates. The greater blue-ringed octopus (*Hapalochlaena lunulata*) and

southern blue-ringed octopus (*H. maculosa*) show five amino acid substitutions (1247T, 1248E, 1526M, 1539H, 1540S) associated with TTX resistance (Fig. 5; Geffeney *et al.*, 2019; Whitelaw *et al.*, 2020). Produced by symbiotic bacteria, this toxin is sequestered by these octopuses in their posterior salivary glands (Sheumack *et al.*, 1978), and in their skin and

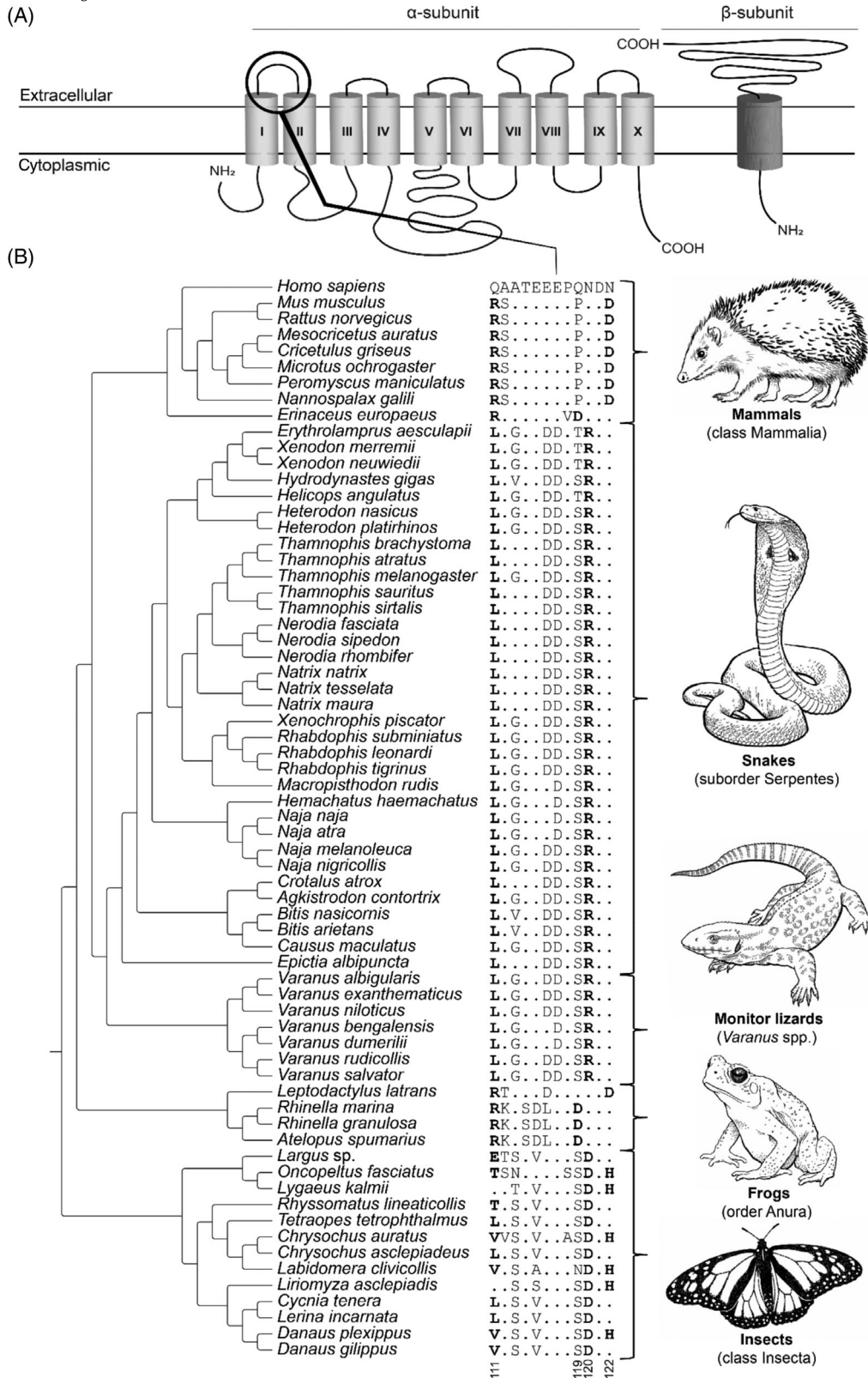


Fig. 6. Convergent evolution of cardiac glycoside resistance in animals. (A) Protein topology of the sodium–potassium pump (Na^+/K^+ -ATPase). The black circle indicates the H1–H2 extracellular loop that is involved in cardiac glycoside binding. Structure based on Bagrov, Shapiro & Fedorova (2009). (B) Sequence alignment of the H1–H2 extracellular domain of Na^+/K^+ -ATPase. The reference amino acid sequence is from humans (*Homo sapiens*) and differences from this sequence are displayed for all other species. Substitutions associated with resistance are highlighted in bold. Tree topology based on TimeTree.org (Kumar *et al.*, 2017) and taxon-specific phylogenies (Dobler *et al.*, 2012; Ujvari *et al.*, 2015; Mohammadi *et al.*, 2016). For sequence accession numbers, see Table S8.

other organs, so TTX is assumed to play a role in both prey capture as well as predator deterrence (Yotsu-Yamashita, Mebs & Flachsenberger, 2007; Williams & Caldwell, 2009). Another example is the soft-shell clam (*Mya arenaria*), which has evolved resistance towards STX, a toxin produced by algal blooms of dinoflagellates (*Alexandrium* spp.; Bricelj *et al.*, 2005; Phillips *et al.*, 2018). Softshell clam populations frequently exposed to blooms have evolved resistance underpinned by an aspartic acid substitution (764D; Fig. 5; Bricelj *et al.*, 2005; Phillips *et al.*, 2018). This resistance increases their capacity to accumulate these toxins, thereby enhancing the risk of paralytic shellfish poisoning after human consumption (Bricelj *et al.*, 2005).

Another relatively underexplored strategy associated with guanidinium toxin resistance involves toxin-binding proteins. The best-studied example is saxiphilin, which is a soluble, well-characterised STX-binding protein (Yen *et al.*, 2019). Saxiphilin has particularly been studied in frogs (Mahar *et al.*, 1991; Yen *et al.*, 2019), but STX-binding activity has also been detected in other amphibians, reptiles, fish and some arthropods (Llewellyn, Bell & Moczydlowski, 1997). By contrast, STX-binding activity has not been detected in any mammal or bird (Llewellyn *et al.*, 1997). Other soluble guanidinium toxin-binding proteins have been identified in pufferfish (Yotsu-Yamashita *et al.*, 2000, 2010), crabs (Lin *et al.*, 2015) and gastropods (Hwang *et al.*, 2007; Takati *et al.*, 2007). Toxin-binding proteins have been identified in plasma, haemolymph, and a diverse range of tissues [e.g., liver, stomach, kidney and heart (Mahar *et al.*, 1991; Llewellyn *et al.*, 1997; Yotsu-Yamashita *et al.*, 2010)]. Remarkably, such toxin-binding proteins not only interact with STX and/or TTX but also with some other small-molecule neurotoxins [e.g. batrachotoxin and decahydroquinoline (Mahar *et al.*, 1991; Llewellyn *et al.*, 1997; Abderemane-Ali *et al.*, 2021; O'Connell *et al.*, 2021)]. Ultimately, toxin-binding proteins such as saxiphilin can provide resistance against guanidinium toxins and are proposed to play a role in sequestration mechanisms that may facilitate autoresistance.

(7) Batrachotoxins

Batrachotoxin (BTX) is a steroidal alkaloid that targets voltage-gated Na⁺ channels (Na_v), causing irreversible depolarisation of muscles and nerves leading to paralysis, cardiac arrest, and other harmful effects (Albuquerque, Daly & Witkop, 1971). Resistance against BTX has evolved in poison dart frogs (family Dendrobatidae) and a few passerine bird species (e.g. *Pitohui* spp.).

Poison dart frogs are known for sequestering a variety of toxins including BTX (Daly, 1995). These frogs selectively sequester such toxins from their diet (Daly *et al.*, 1994; Clark *et al.*, 2005; Saporito *et al.*, 2007b), and these are then used for chemical defence that is generally accompanied by vivid aposematic warning patterns (Summers & Clough, 2001). The golden poison dart frog (*Phyllobates terribilis*), which contains high BTX concentrations in its tissues, shows BTX resistance

(Daly *et al.*, 1980). Partial sequencing of the skeletal muscle Na_v 1.4 channel suggested convergence of several substitutions conferring BTX resistance in poison frogs (Tarvin *et al.*, 2016). Wang & Wang (2017) showed that one of these substitutions reduces BTX sensitivity and suggested that a single amino acid replacement confers BTX resistance. However, a more recent study failed to support the idea that Na_v 1.4 channel mutations confer resistance in poison dart frogs (Abderemane-Ali *et al.*, 2021). It has been hypothesised that these frogs may have autoresistance based on toxin-binding proteins (Abderemane-Ali *et al.*, 2021).

Certain passerine birds native to New Guinea (*Pitohui* spp. and *Ifrita kowaldi*) are known to sequester dietary BTXs (Dumbacher *et al.*, 1992, 2004; Dumbacher, Spande & Daly, 2000). BTXs have been identified in significant concentrations across several organs (e.g. heart, skeletal muscle and liver), but the highest abundance is present in their skin and feathers (Dumbacher, Menon & Daly, 2009). Therefore, BTX is likely utilised for chemical defence against ectoparasites and/or predators (Dumbacher, 1999; Dumbacher *et al.*, 2000). Despite the high concentrations found in these passerine birds, there are no resistance-related modifications in the Na_v channels (Na_v 1.4 and Na_v 1.5, respectively), which could suggest a comparable strategy using toxin-binding proteins as proposed in poison dart frogs (Abderemane-Ali *et al.*, 2021).

(8) Cardiac glycosides

Cardiac glycosides (e.g. cardenolides and bufadienolides) are steroidal compounds that cause cardiotoxicity by inhibiting the sodium–potassium pump (Na⁺/K⁺-ATPase; Schoner, 2002). A variety of animals and plants exploit cardiac glycosides as defensive poisons to deter potential predators (Botelho *et al.*, 2019). As a response, many animals have evolved resistance underpinned by substitutions in the H1–H2 extracellular domain of the Na⁺/K⁺-ATPase (Ujvari *et al.*, 2015; Karageorgi *et al.*, 2019). These substitutions are predominantly characterised by the replacement of neutral amino acids with charged amino acids, causing a reduction in binding affinity of cardiac glycosides (Ujvari *et al.*, 2015). Cardiac glycoside resistance has evolved across the animal kingdom (Fig. 6).

Cardiac glycoside resistance evolved at least twice in mammals (Fig. 6). The European hedgehog (*Erinaceus europaeus*) shows two substitutions (111R and 119D), facilitating predation on cardiac glycoside-containing toads, and could also be associated with the hedgehog's habit of anointing itself with the toad toxins (Brodie, 1977; Ewert & Traud, 1979; Ujvari *et al.*, 2015). Also, some rodents (Muroidea) show resistance characterised by two amino acid substitutions (111R and 122D) – most likely associated with feeding on bufonid toads, insects or plants that contain cardiac glycosides (Ujvari *et al.*, 2015).

Reptiles of the order Squamata have convergently evolved resistance mediated by identical substitutions in their Na⁺/K⁺-ATPase (111L and 120R; Fig. 6; Ujvari *et al.*, 2015; Mohammadi *et al.*, 2016, 2018). This resistant genotype is widespread

across the snake phylogeny, and likely contributes to their ability to prey on toads (Ujvari *et al.*, 2015; Mohammadi *et al.*, 2016). Interestingly, keelback snakes (*Rhabdophis* spp.) not only consume toxin-bearing amphibians, but they also sequester these toxins in their nuchal glands for antipredator defence (Hutchinson *et al.*, 2007; Mori *et al.*, 2012). Additionally, varanid lizards (*Varanus* spp.) native to Africa and Asia that occasionally feed on toxin-bearing toads also have evolved this resistant genotype (Ujvari *et al.*, 2013). However, their Australian congeners, which originally did not share their habitat with bufonid toads, were found to have a reversal of this genotype (Ujvari *et al.*, 2013, 2015). This lack of resistance in Australian varanid lizards resulted in major population declines after the introduction of the invasive cane toad (*Rhinella marina*), on which they occasionally predate (Madsen & Ujvari, 2009; Jolly, Shine & Greenlees, 2015).

Amphibians of the order Anura have convergently evolved resistance towards cardiac glycosides on two occasions (Ujvari *et al.*, 2015). Bufonid toads (family Bufonidae) evolved resistance under strong positive selection based on two substitutions in Na⁺/K⁺-ATPase (111R and 119D; Fig. 6) – presumably enabling the synthesis of their cardiac glycosides which they exploit to deter aggressors (Moore *et al.*, 2009; Ujvari *et al.*, 2015). By contrast, the South American spotted grassfrog (*Leptodactylus latrans*) evolved two substitutions in Na⁺/K⁺-ATPase (111R and 122D; Fig. 6), allowing them to feed upon otherwise chemically protected bufonid prey (Ujvari *et al.*, 2015; Mohammadi *et al.*, 2021).

Another example of resistance in invertebrates is provided by insects (class Insecta). At least 21 lineages of insects have independently evolved the ability to feed on plants that contain cardiac glycosides and to sequester those toxins (Karageorgi *et al.*, 2019). These feeding habits are facilitated by toxin resistance underpinned by combinations of two or three substitutions at residues 111, 120 and/or 122 in Na⁺/K⁺-ATPase (111E, 111T, 111L, 111V, 120D, and/or 122H; Fig. 6; Holzinger, Frick & Wink, 1992; Dobler *et al.*, 2012; Zhen *et al.*, 2012; Ujvari *et al.*, 2015; Karageorgi *et al.*, 2019).

(9) Epibatidine

Epibatidine is an alkaloid toxin that targets neural-type nicotinic acetylcholine receptors (nAChRs), causing muscle paralysis (Tarvin *et al.*, 2017). This rarely observed form of resistance has evolved independently in distinct poison dart frog lineages. Poison dart frogs are known to exploit multiple toxins, including epibatidine, for chemical defence (Daly, 1995). Three distinct dendrobatid frog clades (*Oophaga* spp., *Ameerega* spp., and *Epipedobates* spp.) have convergently evolved resistance mediated by a single amino acid replacement to a cysteine in the β2 subunit of neural-type nAChR (108C; Fig. 7; Tarvin *et al.*, 2017). The cysteine residue has a sulphur-containing side chain that is bulkier compared to the naïve serine residue. This substitution occurs at a key position for epibatidine binding and is therefore hypothesised to alter the epibatidine–receptor interaction (Tarvin *et al.*, 2017). Additionally, another amino acid replacement to a valine (118V) in the *Ameerega* lineage has also been shown to

reduce epibatidine binding (Fig. 7; Tarvin *et al.*, 2017). The resistant phenotype might allow storage of epibatidine in the granular skin glands, which subsequently can be used for deterring adversaries.

III EVOLUTIONARY IMPLICATIONS OF TOXIN RESISTANCE

(1) When does toxin resistance evolve?

Prey and predator inevitably exert reciprocal selection pressures on each other. A prey species is under selection to avoid capture, whereas a predator is under selection to acquire the energy resources contained in the prey. In any predator–prey relationship involving a poisonous or venomous participant, this will translate into selection to evade these toxic armaments. Given sufficient reciprocal selection, this can in turn trigger an evolutionary response in the toxic participant to maintain the effectiveness of its weaponry, potentially leading to an evolutionary arms race.

The intensity and symmetry of selective forces between prey and predator are highly variable, depending on the importance of the prey species as a resource to the predator, and the importance of the predator as a cause of loss in fitness to the prey. For example, as we discussed above, some animals show a reversal of their resistant genotype in the absence of their toxic counterparts (Ujvari *et al.*, 2015; Khan *et al.*, 2020).

Life-history theory predicts that toxin resistance is most likely to evolve when the poisonous or venomous opponent exerts strong selection, whether as prey or as predator. In predators of toxic prey, resistance is most likely to evolve when the predator is under strong selection to exploit an abundant but toxic food source. Examples include many reptiles that prey on toxic amphibians (Feldman *et al.*, 2012; Ujvari *et al.*, 2015), mammalian mesopredators feeding on venomous snakes (Drabeck *et al.*, 2015, 2020) and grasshopper mice eating bark scorpions (Rowe *et al.*, 2013). In prey species subject to predation by a venomous predator, prey resistance will most likely evolve if the predator is an important overall cause of mortality, e.g. sea kraits (*Laticauda* spp.), a lineage unrelated to other sea snakes, preying on moray eels (*Gymnothorax* spp. Heatwole & Poran, 1995) and rattlesnakes preying on North American ground squirrels and other rodents (de Wit, 1982; Holding *et al.*, 2016a; Gibbs *et al.*, 2020). In the latter example, reciprocal adaptation has been demonstrated, as rattlesnakes match their venom phenotype to the resistance profile of local prey to retain a selective advantage (Holding *et al.*, 2016a; Margres *et al.*, 2017), contrary to the predictions of the ‘Life-Dinner Principle’ (Dawkins *et al.*, 1979). That principle implies asymmetric selection, such that the prey is under greater selection pressure to escape capture, compared to the selection pressure on the predator to secure a meal.

By contrast, life-history theory predicts that resistance is unlikely to evolve when selection pressure is low, for example:

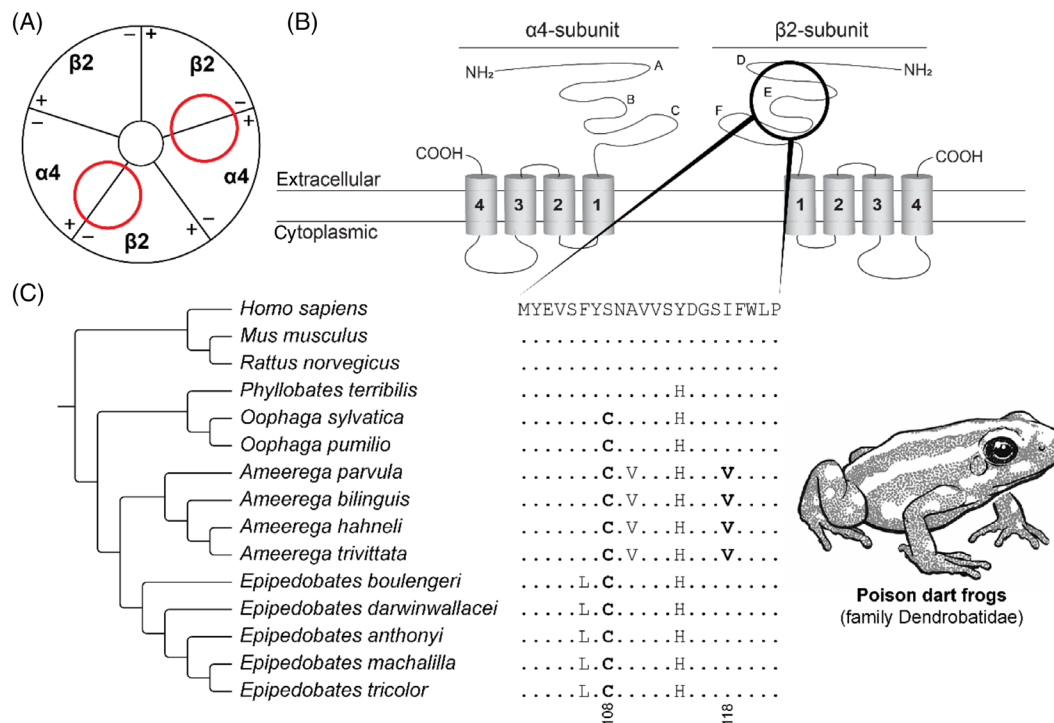


Fig. 7. Convergent evolution of epibatidine resistance in poison dart frogs. (A) Schematic representation (based on Kini, 2019) of the neural-type nicotinic acetylcholine receptor [nAChR; $(\alpha 4)_2(\beta 2)_3$]. Red circles indicate the ligand-binding domain of epibatidine in the nAChR. (B) Protein topology of the $\alpha 4$ -subunit and the $\beta 2$ -subunit of the neural-type nAChR. A–F indicate the loop structures at the extracellular domain in the respective subunits (Rahman *et al.*, 2020). The black circle indicates the E-loop involving the ligand-binding domain of epibatidine. (C) Sequence alignment of the $\beta 2$ -nAChR ligand-binding domain. The reference amino acid sequence is from humans (*Homo sapiens*) and differences from this sequence are displayed for all other species. Substitutions associated with resistance are highlighted in bold. Tree topology based on Tarvin *et al.* (2017). For sequence accession numbers, see Table S9.

(i) when predation by a venomous predator is a relatively unimportant selective force for the prey because of the scarcity of encounters; (ii) a short temporal window of exposure exists (Marques *et al.*, 2012); or (iii) when behavioural avoidance of toxic prey is more advantageous than evolving resistance (Smith, 1977; Brodie III, 1993; Portugal *et al.*, 2016); see also Fig. 3).

Finally, it is also possible that resistance is most likely to evolve in situations where incremental increases in resistance confer an increasing selective advantage. Relatively low-level resistance could be adaptive where prey toxicity varies geographically (Feldman *et al.*, 2012). It could also be adaptive where different life stages differ in their toxin content, as appears to be the case in cane toads (*Rhinella marina*), for example (Hayes *et al.*, 2009). Finally, low-level resistance could be adaptive where partial failure of predatory envenomation is common, as seen in venomous snakes (Whitford *et al.*, 2019). In summary, resistance is seen in many diverse ecological contexts and can be interpreted under a range of evolutionary scenarios. Despite the complex routes towards resistance, a few outcomes are repeatedly seen in unrelated lineages.

(2) Competing selection pressures and convergent evolution

Evolutionary trade-offs usually come with a fitness disadvantage (Brodie III & Brodie Jr, 1999; Blanchard & Moreau, 2017; Hague *et al.*, 2018). It is important that resistance modifications do not disrupt the physiology of the resistant animal. Therefore, there is a trade-off between a functional target (e.g. binding site of the endogenous ligand) and the modifications enhancing toxin resistance. The emergence of similar adaptations is likely mediated by constraints on a functional target when subjected to similar selection pressures. Some examples of this can be seen across the animal kingdom.

Poison dart frog clades convergently evolved an identical substitution conferring epibatidine-resistance, causing a decrease in acetylcholine sensitivity. As a result, this was then compensated by additional substitutions to maintain the receptor function (Tarvin *et al.*, 2017). A similar phenomenon can be observed in α -neurotoxin resistance. Multiple substitutions convergently evolved to reduce α -neurotoxin binding but without compromising the amino acid residues vital for acetylcholine binding (Barchan *et al.*, 1992; Khan *et al.*, 2020). Similar convergent adaptations are found in multiple

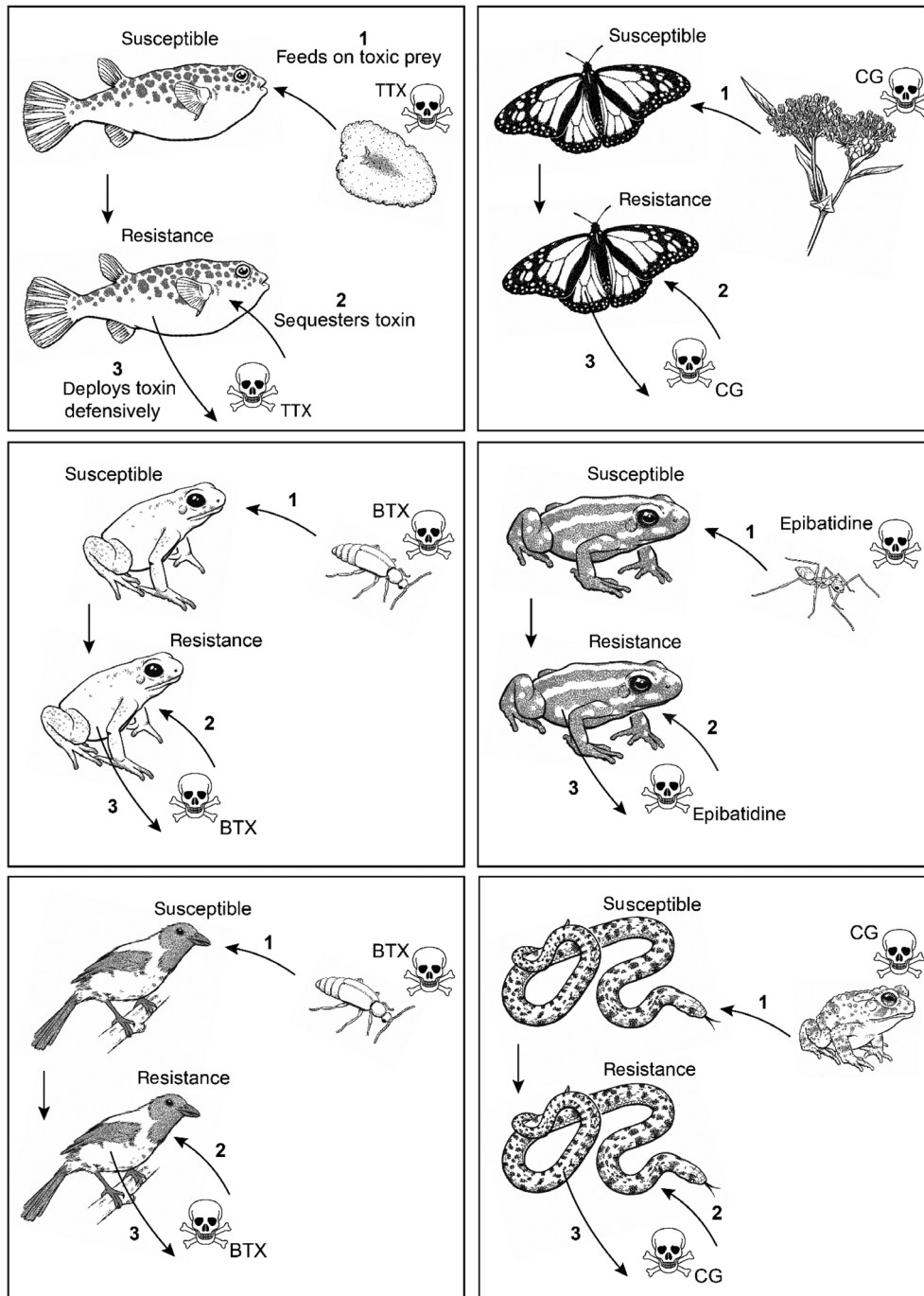


Fig. 8. Hypothesised convergent evolutionary scenarios for autoresistance in poisonous animals. It is generally assumed that autoresistance is a self-protection phenomenon. Here, we propose a three-step evolution scenario for the origins of autoresistance: (1) predator resistance, followed by (2) sequestration of the toxin by the predator, and (3) exploitation of the toxin for defence. As this figure indicates, a similar three-step process can be seen in diverse lineages, suggesting evolutionary convergence. The displayed examples include (A) pufferfish (family Tetraodontidae) feeding on TTX-bearing flatworms, gastropods and echinoderms, (B) herbivorous insects feeding on CG-containing plants, (C, D) poison dart frogs (family Dendrobatidae) feeding on toxic arthropods, (E) pitohui birds (*Pitohui* spp.) feeding on (among others) BTX-bearing melyrid beetles, and (F) keelback snakes (*Rhabdophis* spp.) feeding on CG-bearing anuran amphibians. BTX, batrachotoxin; CG, cardiac glycosides; TTX, tetrodotoxin.

distinct colubrid snakes showing tetrodotoxin resistance. This trait is mediated by a functional trade-off between ion channel function and tetrodotoxin insensitivity (Lee *et al.*, 2011; Feldman *et al.*, 2012). Cardiac glycoside resistance consistently evolved many times by two or three substitutions (respectively positioned at 111, 119, 120 or 122) – suggesting that these widespread genotypes also are constrained (Dobler *et al.*, 2012; Ujvari *et al.*, 2015; Karageorgi *et al.*, 2019).

In summary, toxin resistance shows fascinating examples of non-random and deterministic evolution mediated by constraints on sequence plasticity, while retaining receptor functionality. Thus, there may be a limited number of functional amino acid substitutions that reduce the binding affinity of toxins, even when different species are under similar selection pressures. This limited number of functional solutions available for adaptive evolution results in repeated funnelling of the same molecular pathway, leading to convergence.

(3) Origins of autoresistance in poisonous animals

Some animals are resistant to their own toxins, referred to as autoresistance. Venomous animals likely evolved resistance both for the prevention of self-venomation (autoresistance) and for defence against other venomous animals (see Section II.(4)). However, we suggest that this is a much more complicated evolutionary scenario in the case of poisons (e.g. tetrodotoxin, cardiac glycosides, batrachotoxin, epibatidine) – which has already been partially touched upon in previous literature (Saporito *et al.*, 2012; Santos, Tarvin & O'Connell, 2016). We propose a scenario in which there was a three-step evolution of resistance across phylogenetically distinct poisonous animals: (i) predator resistance, followed by (ii) sequestration of the toxin by the predator, and finally (iii) exploitation of the toxin for defence (Fig. 8).

Over the course of evolution, predation on a toxic species leads to frequent exposure to one or more specific toxins through generalised trophic interactions. In most cases, naïve predators feeding on highly toxic prey (such as TTX-containing newts) are rapidly eliminated, with negative selection on the wild type thus favouring toxic prey avoidance. However, if variants that are capable of tolerating potent toxins exist in the population, then positive selection should favour the resistant phenotype, as this allows the predator to capitalise on abundant, often underutilised prey species. This then provides an evolutionary selection pressure on evolving, and maybe in some cases even maintaining, a less-susceptible genotype. Interestingly, several animals (e.g. poison dart frogs and pufferfish) have been shown to be toxic only after the ingestion of a toxic diet, indicating that the toxins originated exogenously (Noguchi *et al.*, 2006a; Saporito *et al.*, 2007a; Yotsu-Yamashita *et al.*, 2012). Subsequently, the resistant phenotype increases the accumulation capacity of the toxin compared to non-resistant animals (for example, as observed in clams; Bricelj *et al.*, 2005). This phenomenon is not likely to occur in predators of venomous animals due to the proteinaceous nature of venom toxins that are easily metabolised after ingestion. By contrast, poisons

(e.g. alkaloid or steroidal-based toxins) are less easily metabolised and thus accumulate in the body. Ultimately, this enabled the exploitation of the accumulated toxins for defensive purposes in poisonous animals (reviewed in Savitzky *et al.*, 2012). Therefore, we hypothesise that autoresistance primarily evolved as predator resistance rather than as an evolutionary driver itself, suggesting that multiple widespread taxa convergently evolved this three-step evolution of resistance (Fig. 8).

IV CONCLUSIONS

(1) Toxin resistance is an adaptive response seen at many trophic levels, underscoring how relatively simple adaptations can lead to solutions to complicated problems. This review has shown that molecular adaptations conferring toxin resistance have evolved repeatedly in diverse animal lineages, highlighting how different selection pressures can result in convergence at the molecular level.

(2) Convergent evolution involving toxin resistance can be explained by functional constraints. These constraints are mediated by a trade-off between maintaining a functional molecular target and reducing toxin susceptibility. This trade-off limits the functional solutions available for adaptive evolution.

(3) We propose a novel scenario for the evolution of 'autoresistance' in poisonous animals. We suggest that autoresistance did not evolve primarily as a form of self-protection, but as a consequence of those animals feeding on toxic prey. This would imply that multiple diverse taxa convergently evolved this scenario.

(4) Similar selection pressures do not always lead to convergent molecular adaptations (as shown in certain bird, mammal, and reptile species). Molecular adaptations are only one of the ways in which organisms deal with toxins. We propose that some animals have elaborated or exploited existing behavioural or morphological traits, which may be exaptations, as alternative strategies to prevent intoxication in the first place.

(5) Toxin resistance is a phenomenon existing at the crossroads between molecular evolution, selection pressures and ecological interactions. The emergence of new or improved research technologies (e.g. -omics, functional assays and genetic modification techniques), combined with more robust ecological models, will provide opportunities to study novel and unexplored forms of resistance, as well as fundamental knowledge on how animals cope with direct or indirect exposure to toxic molecules in their environment. Toxin resistance is a compelling and multidisciplinary model system for studying evolutionary novelties with relevance in many branches of biology.

V ACKNOWLEDGEMENTS

M. A. K. and M. K. R. were supported by Elise Mathilde Fonds of Leids Universiteits Fonds (grant number

6113/21-6-16), Academy Ecology Funds of Royal Netherlands Academy of Arts and Sciences (grant number 713/18015), Higher Education Commission, Islamabad, Pakistan; R. J. H. was supported by the University of Queensland International PhD scholarship fund; and R. M. K. was supported by Ministry of Education, Singapore (grant number MOE2017-T2-1-045). All line drawings of animals and plants were created by Sven Ballinger.

VI. REFERENCES

- References marked with asterisk have been cited within the supporting information
- ABDEREMANE-ALI, F., ROSSEN, N. D., KOBIELA, M. E., CRAIG, R. A. II, GARRISON, C. E., CHEN, Z., COLLERAN, C. M., O'CONNELL, L. A., DU BOIS, J., DUMBACHER, J. P. & MINOR, D. L. JR. (2021). Evidence that toxin resistance in poison birds and frogs is not rooted in sodium channel mutations and may rely on "toxin sponge" proteins. *Journal of General Physiology* **153**, 1–20.
- ALBUQUERQUE, E. X., DALY, J. W. & WITKOP, B. (1971). Batrachotoxin: chemistry and pharmacology. *Science* **172**, 995–1002.
- ALEXANDER, G. J. & MARITZ, B. (2010). *Bitis arietans arietans*: partial resistance to *Naja* venom. *African Herp News* **50**, 34–36.
- ALMEIDA-SANTOS, S. M., ANTONIAZZI, M. M., SANT'ANNA, O. A. & JARED, C. (2000). Predation by the opossum *Didelphis marsupialis* on the rattlesnake *Crotalus durissus*. *Current Herpetology* **19**, 1–9.
- ARÁOZ, R., MOLGÓ, J. & TANDEAU DE MARSAC, N. (2010). Neurotoxic cyanobacterial toxins. *Toxicon* **56**, 813–828.
- ARBUCKLE, K., RODRIGUEZ DE LA VEGA, R. C. & CASEWELL, N. R. (2017). Coevolution takes the sting out of it: evolutionary biology and mechanisms of toxin resistance in animals. *Toxicon* **140**, 118–131.
- ASHER, O., LUPU-MEIRI, M., JENSEN, B. S., PAPERNA, T., FUCHS, S. & ORON, Y. (1998). Functional characterization of mongoose nicotinic acetylcholine receptor alpha-subunit: resistance to alpha-bungarotoxin and high sensitivity to acetylcholine. *FEBS Letters* **431**, 411–414.
- BAGROV, A. Y., SHAPIRO, J. I. & FEDOROVA, O. V. (2009). Endogenous cardiotonic steroids: physiology, pharmacology, and novel therapeutic targets. *Pharmacological Reviews* **61**, 9–38.
- BARCHAN, D., KACHALSKY, S., NEUMANN, D., VOGEL, Z., OVADIA, M., KOCHVA, E. & FUCHS, S. (1992). How the mongoose can fight the snake: the binding site of the mongoose acetylcholine receptor. *Proceedings of the National Academy of Sciences of the United States of America* **89**, 7717–7721.
- BARCHAN, D., OVADIA, M., KOCHVA, E. & FUCHS, S. (1995). The binding site of the nicotinic acetylcholine receptor in animal species resistant to α -bungarotoxin. *Biochemistry* **34**, 9172–9176.
- BEGG, C. M., BEGG, K. S., DU TOIT, J. T. & MILLS, M. G. L. (2003). Sexual and seasonal variation in the diet and foraging behaviour of a sexually dimorphic carnivore, the honey badger (*Mellivora capensis*). *Journal of Zoology* **260**, 301–316.
- BELL, G. (1982). Behavioral and ecological aspects of gleaning by a desert insectivorous bat *Antrozous pallidus* (Chiroptera: Vespertilionidae). *Behavioral Ecology and Sociobiology* **10**, 217–223.
- BIARDI, J. E. & COSS, R. G. (2011). Rock squirrel (*Spermophilus variegatus*) blood sera affects proteolytic and hemolytic activities of rattlesnake venoms. *Toxicon* **57**, 323–331.
- BIARDI, J., HO, C., MARCINCYK, J. & NAMBIAR, K. (2011). Isolation and identification of a snake venom metalloproteinase inhibitor from California ground squirrel (*Spermophilus beecheyi*) blood sera. *Toxicon* **58**, 486–493.
- BLANCHARD, B. D. & MOREAU, C. S. (2017). Defensive traits exhibit an evolutionary trade-off and drive diversification in ants. *Evolution* **71**, 315–328.
- *BORKOW, G., GUTIERREZ, J. M. & OVADIA, M. (1994). A potent antihemorrhagin in the serum of the non-poisonous water snake *Natrix tessellata*: isolation, characterization and mechanism of neutralization. *Biochimica et Biophysica Acta* **1201**, 482–490.
- *BORKOW, G., GUTIERREZ, J. M. & OVADIA, M. (1995). Isolation, characterization and mode of neutralization of a potent antihemorrhagic factor from the serum of the snake *Bothrops asper*. *Biochimica et Biophysica Acta* **1245**, 232–238.
- BOTELHO, A. F. M., PIEREZAN, F., SOTO-BLANCO, B. & MELO, M. M. (2019). A review of cardiac glycosides: structure, toxicokinetics, clinical signs, diagnosis and antineoplastic potential. *Toxicon* **158**, 63–68.
- BRICELJ, V. M., CONNELL, L., KONOKI, K., MACQUARRIE, S. P., SCHEUER, T., CATTERALL, W. A. & TRAINER, V. L. (2005). Sodium channel mutation leading to saxitoxin resistance in clams increases risk of PSP. *Nature* **434**, 763–767.
- BRODIE, E. D. (1977). Hedgehogs use toad venom in their own defence. *Nature* **268**, 627–628.
- BRODIE, E. D. (1990). Tetrodotoxin resistance in garter snakes: an evolutionary response of predators to dangerous prey. *Evolution* **44**, 651–659.
- BRODIE, E. D. III (1993). Differential avoidance of coral snake banded patterns by free-ranging avian predators in Costa Rica. *Evolution* **47**, 227–235.
- BRODIE, E. D. III & BRODIE, E. D. JR. (1999). Costs of exploiting poisonous prey: evolutionary trade-offs in a predator-prey arms race. *Evolution* **53**, 626–631.
- BRODIE, E. D. III & BRODIE, E. D. JR. (1999). Predator-prey arms races: asymmetrical selection on predators and prey may be reduced when prey are dangerous. *Bioscience* **49**, 557–568.
- BRODIE, E. D. III, FELDMAN, C. R., HANIFIN, C. T., MOTYCHAK, J. E., MULCAHY, D. G., WILLIAMS, B. L. & BRODIE, E. D. JR. (2005). Parallel arms races between garter snakes and newts involving tetrodotoxin as the phenotypic interface of coevolution. *Journal of Chemical Ecology* **31**, 343–356.
- CASEWELL, N. R., WÜSTER, W., VONK, F. J., HARRISON, R. A. & FRY, B. G. (2013). Complex cocktails: the evolutionary novelty of venoms. *Trends in Ecology & Evolution* **28**, 219–229.
- CASEWELL, N. R., PETRAS, D., CARD, D. C., SURANSE, V., MYCHAJLIW, A. M., RICHARDS, D., KOLUDAROV, I., ALBULESCU, L.-O., SLAGBOOM, J., HEMPEL, B.-F., NGUM, N. M., KENNERLEY, R. J., BROCCA, J. L., WHITELEY, G., HARRISON, R. A., BOLTON, F. M. S., et al. (2019). Solenodon genome reveals convergent evolution of venom in eulipotyphlan mammals. *Proceedings of the National Academy of Sciences of the United States of America* **116**, 25745–25755.
- *CATANESE, J. J. & KRESS, L. F. (1992). Isolation from opossum serum of a metalloproteinase inhibitor homologous to human alpha 1B-glycoprotein. *Biochemistry* **31**, 410–418.
- CLARK, V. C., RAXWORTHY, C. J., RAKOTOMALALA, V., SIERWALD, P. & FISHER, B. L. (2005). Convergent evolution of chemical defense in poison frogs and arthropod prey between Madagascar and the Neotropics. *Proceedings of the National Academy of Sciences of the United States of America* **102**, 11617–11622.
- DALY, J. W. (1995). The chemistry of poisons in amphibian skin. *Proceedings of the National Academy of Sciences of the United States of America* **92**, 9–13.
- DALY, J. W., MYERS, C. W., WARNICK, J. E. & ALBUQUERQUE, E. X. (1980). Levels of batrachotoxin and lack of sensitivity to its action in poison-dart frogs (*Phylllobates*). *Science* **208**, 1383–1385.
- DALY, J. W., SECUNDA, S. I., GARRAFFO, H. M., SPANDE, T. F., WISNIESKI, A. & COVER, J. F. (1994). An uptake system for dietary alkaloids in poison frogs (Dendrobatidae). *Toxicon* **32**, 657–663.
- DAWKINS, R., KREBS, J. R., MAYNARD SMITH, J. & HOLLIDAY, R. (1979). Arms races between and within species. *Proceedings of the Royal Society of London. Series B. Biological Sciences* **205**, 489–511.
- DELLISANTI, C., YAO, Y., STROUD, J. C., WANG, Z.-Z. & CHEN, L. (2007). Structural determinants for α -neurotoxin sensitivity in muscle nAChR and their implications for the gating mechanism. *Channels* **1**, 234–237.
- DOBLER, S., DALLA, S., WAGSCHAL, V. & AGRAWAL, A. A. (2012). Community-wide convergent evolution in insect adaptation to toxic cardenolides by substitutions in the Na,K-ATPase. *Proceedings of the National Academy of Sciences of the United States of America* **109**, 13040–13045.
- DRABECK, D. H., DEAN, A. M. & JANSÁ, S. A. (2015). Why the honey badger don't care: convergent evolution of venom-targeted nicotinic acetylcholine receptors in mammals that survive venomous snake bites. *Toxicon* **99**, 68–72.
- DRABECK, D. H., RUCAVADO, A., HINGSAH-ZAHER, E., CRUZ, Y. P., DEAN, A. M. & JANSÁ, S. A. (2020). Resistance of South American opossums to vWF-binding venom C-type lectins. *Toxicon* **178**, 92–99.
- DUAN, J., SANGGAARD, K. W., SCHAUSER, L., LAURIDSEN, S. E., ENGHILD, J. J., SCHIERUP, M. H. & WANG, T. (2017). Transcriptome analysis of the response of Burmese python to digestion. *GigaScience* **6**, 1–18.
- DUMBACHER, J. P. (1999). Evolution of toxicity in pitohuis: I. Effects of homobatrachotoxin on chewing lice (order Phthiraptera). *The Auk* **116**, 957–963.
- DUMBACHER, J. P., BEEHLER, B. M., SPANDE, T. F., GARRAFFO, H. M. & DALY, J. W. (1992). Homobatrachotoxin in the genus *Pitohui*: chemical defense in birds? *Science* **258**, 799–801.
- DUMBACHER, J. P., SPANDE, T. F. & DALY, J. W. (2000). Batrachotoxin alkaloids from passerine birds: a second toxic bird genus (*Irita kowaldi*) from New Guinea. *Proceedings of the National Academy of Sciences of the United States of America* **97**, 12970–12975.
- DUMBACHER, J. P., WAKO, A., DERRICKSON, S. R., SAMUELSON, A., SPANDE, T. F. & DALY, J. W. (2004). Melyrid beetles (Choresine): a putative source for the batrachotoxin alkaloids found in poison-dart frogs and toxic passerine birds. *Proceedings of the National Academy of Sciences of the United States of America* **101**, 15857–15860.
- DUMBACHER, J. P., MENON, G. K. & DALY, J. W. (2009). Skin as a toxin storage organ in the endemic New Guinean genus *Pitohui*. *The Auk* **126**, 520–530.
- DURAN-RIVEROLL, L. M. & CEMBELLA, A. D. (2017). Guanidinium toxins and their interactions with voltage-gated sodium ion channels. *Marine Drugs* **15**, 1–28.

- *ESTEVAO-COSTA, M. I., ROCHA, B. C., DE ALVARENGA MUDADO, M., REDONDO, R., FRANCO, G. R. & FORTES-DIAS, C. L. (2008). Prospection, structural analysis and phylogenetic relationships of endogenous γ -phospholipase A2 inhibitors in Brazilian *Bothrops* snakes (Viperidae, Crotalinae). *Toxicon* **52**, 122–129.
- EWERT, J. P. & TRAUD, R. (1979). Releasing stimuli for antipredator behaviour in the Common Toad *Bufo bufo* (L.). *Behaviour* **68**, 170–180.
- *FARAH, M. F., ONE, M., NOVELLO, J. C., TOYAMA, M. H., PERALES, J., MOUSSATCHE, H., DOMONT, G. B., OLIVEIRA, B. & MARANGONI, S. (1996). Isolation of protein factors from opossum (*Didelphis albiventris*) serum which protect against *Bothrops jararaca* venom. *Toxicon* **34**, 1067–1071.
- FELDMAN, C. R., BRODIE, E. D. JR., BRODIE, E. D. III & PFRENDER, M. E. (2009). The evolutionary origins of beneficial alleles during the repeated adaptation of garter snakes to deadly prey. *Proceedings of the National Academy of Sciences of the United States of America* **106**, 13415–13420.
- FELDMAN, C. R., BRODIE, E. D., BRODIE, E. D. & PFRENDER, M. E. (2010). Genetic architecture of a feeding adaptation: garter snake (*Thamnophis*) resistance to tetrodotoxin bearing prey. *Proceedings of the Royal Society B: Biological Sciences* **277**, 3317–3325.
- FELDMAN, C. R., BRODIE, E. D., BRODIE, E. D. & PFRENDER, M. E. (2012). Constraint shapes convergence in tetrodotoxin-resistant sodium channels of snakes. *Proceedings of the National Academy of Sciences of the United States of America* **109**, 4556–4561.
- FELDMAN, C. R., DURSO, A. M., HANIFIN, C. T., PFRENDER, M. E., DUCEY, P. K., STOKES, A. N., BARNETT, K. E., BRODIE, E. D. III & BRODIE, E. D. JR. (2016). Is there more than one way to skin a newt? Convergent toxin resistance in snakes is not due to a common genetic mechanism. *Heredity* **116**, 84–91.
- FERRAZ, C. R., ARRAHMAN, A., XIE, C., CASEWELL, N. R., LEWIS, R. J., KOOL, J. & CARDOSO, F. C. (2019). Multifunctional toxins in snake venoms and therapeutic implications: from pain to hemorrhage and necrosis. *Frontiers in Ecology and Evolution* **7**, 1–19.
- *FORTES-DIAS, C. L., FONSECA, B. C. B., KOCHVA, E. & DINIZ, C. R. (1991). Purification and properties of an antivenom factor from the plasma of the south American rattlesnake (*Crotalus durissus terrificus*). *Toxicon* **29**, 997–1008.
- *FORTES-DIAS, C. L., BARCELLOS, C. J. & ESTEVAO-COSTA, M. I. (2003). Molecular cloning of a γ -phospholipase A2 inhibitor from *Lachesis muta muta* (the bushmaster snake). *Toxicon* **41**, 909–917.
- FORTES-DIAS, C. L., MACEDO, D. H. F., BARBOSA, R. P., SOUZA-SILVA, G. & ORTOLANI, P. L. (2020). Identification and characterization of the first endogenous phospholipase A2 inhibitor from a non-venomous tropical snake, *boa constrictor* (Serpentes: Boidae). *Journal of Venomous Animals and Toxins Including Tropical Diseases* **26**, 1–9.
- FRY, B. G., ROELANTS, K., CHAMPAGNE, D. E., SCHEIB, H., TYNDALL, J. D., KING, G. F., NEVALAINEN, T. J., NORMAN, J. A., LEWIS, R. J., NORTON, R. S., RENJIFO, C. & DE LA VEGA, R. C. (2009). The toxicogenomic multiverse: convergent recruitment of proteins into animal venoms. *Annual Review of Genomics and Human Genetics* **10**, 483–511.
- GARCIA, V. E. & PEREZ, J. C. (1984). The purification and characterization of an antihemorrhagic factor in woodrat (*Neotoma micropus*) serum. *Toxicon* **22**, 129–138.
- GEFFENEY, S., BRODIE, E. D. & RUBEN, P. C. (2002). Mechanisms of adaptation in a predator–prey arms race: TTX-resistant sodium channels. *Science* **297**, 1336–1339.
- GEFFENEY, S. L., FUJIMOTO, E., BRODIE, E. D., BRODIE, E. D. & RUBEN, P. C. (2005). Evolutionary diversification of TTX-resistant sodium channels in a predator–prey interaction. *Nature* **434**, 759–763.
- GEFFENEY, S. L., WILLIAMS, B. L., ROSENTHAL, J. J. C., BIRK, M. A., FELKINS, J., WISELL, C. M., CURRY, E. R. & HANIFIN, C. T. (2019). Convergent and parallel evolution in a voltage-gated sodium channel underlies TTX-resistance in the greater blue-ringed octopus *Hapalochlaena lunulata*. *Toxicon* **170**, 77–84.
- GENDREAU, K. L., HORNSBY, A. D., HAGUE, M. T. J. & MCGLOTHLIN, J. W. (2021). Gene conversion facilitates the adaptive evolution of self-resistance in highly toxic newts. *Molecular Biology and Evolution* **38**, 4077–4094.
- GIBBS, H. L., SANZ, L., PEREZ, A., OCHOA, A., HASSINGER, A. T. B., HOLDING, M. L. & CALVETE, J. J. (2020). The molecular basis of venom resistance in a rattlesnake-squirrel predator-prey system. *Molecular Ecology* **29**, 2871–2888.
- GOETZ, S. M., PICCOLOMINI, S., HOFFMAN, M., BOGAN, J., HOLDING, M. L., MENDONÇA, M. T. & STEEN, D. A. (2019). Serum-based inhibition of pitviper venom by eastern indigo snakes (*Drymarchon couperi*). *Biology Open* **8**, 1–5.
- HAGUE, M. T. J., TOLEDO, G., GEFFENEY, S. L., HANIFIN, C. T., BRODIE, E. D. JR. & BRODIE, E. D. III (2018). Large-effect mutations generate trade-off between predatory and locomotor ability during arms race coevolution with deadly prey. *Evolution Letters* **2**, 406–416.
- *HAINS, P. G. & BROADY, K. W. (2000). Purification and inhibitory profile of phospholipase A2 inhibitors from Australian elapid sera. *Biochemical Journal* **346**, 139–146.
- HANIFIN, C. T. & GILLY, W. F. (2015). Evolutionary history of a complex adaptation: tetrodotoxin resistance in salamanders. *Evolution* **69**, 232–244.
- HARRIS, R. J. & FRY, B. G. (2021). Electrostatic resistance to alpha-neurotoxins conferred by charge reversal mutations in nicotinic acetylcholine receptors. *Proceedings of the Royal Society B: Biological Sciences* **288**, 1–8.
- HARRIS, R. J., NEKARIS, K. A.-I. & FRY, B. G. (2021). Monkeying around with venom: an increased resistance to α -neurotoxins supports an evolutionary arms race between afro-Asian primates and sympatric cobras. *BMC Biology* **19**, 1–13.
- HAYES, R. A., CROSSLAND, M. R., HAGMAN, M., CAPON, R. J. & SHINE, R. (2009). Ontogenetic variation in the chemical defenses of cane toads (*Bufo marinus*): toxin profiles and effects on predators. *Journal of Chemical Ecology* **35**, 391–399.
- HEATWOLE, H. & PORAN, N. S. (1995). Resistances of sympatric and allopatric eels to sea snake venoms. *Copeia* **1995**, 136–147.
- HOLDING, M. L., BIARDI, J. E. & GIBBS, H. L. (2016a). Coevolution of venom function and venom resistance in a rattlesnake predator and its squirrel prey. *Proceedings of the Royal Society B: Biological Sciences* **283**, 1–9.
- HOLDING, M. L., DRABECK, D. H., JANSA, S. A. & GIBBS, H. L. (2016b). Venom resistance as a model for understanding the molecular basis of complex coevolutionary adaptations. *Integrative and Comparative Biology* **56**, 1032–1043.
- HOLZINGER, F., FRICK, C. & WINK, M. (1992). Molecular basis for the insensitivity of the monarch (*Danaus plexippus*) to cardiac glycosides. *FEBS Letters* **314**, 477–480.
- HOOD, L., KRONENBERG, M. & HUNKAPILLER, T. (1985). T cell antigen receptors and the immunoglobulin supergene family. *Cell* **40**, 225–229.
- HOPP, B. H., ARVIDSON, R. S., ADAMS, M. E. & RAZAK, K. A. (2017). Arizona bark scorpion venom resistance in the pallid bat, *Antrozous pallidus*. *PLoS One* **12**, 1–13.
- *HUANG, K.-F., CHOW, L.-P. & CHIOU, S.-H. (1999). Isolation and characterization of a novel proteinase inhibitor from the snake serum of Taiwan habu (*Trimeresurus mucrosquamatus*). *Biochemical and Biophysical Research Communications* **263**, 610–616.
- HUTCHINSON, D. A., MORI, A., SAVITZKY, A. H., BURGHARDT, G. M., WU, X., MEINWALD, J. & SCHROEDER, F. C. (2007). Dietary sequestration of defensive steroids in nuchal glands of the Asian snake *Rhabdophis tigrinus*. *Proceedings of the National Academy of Sciences of the United States of America* **104**, 2265–2270.
- HWANG, D. F., ARAKAWA, O., SAITO, T., NOGUCHI, T., SMIDU, U., TSUKAMOTO, K., SHIDA, Y. & HASHIMOTO, K. (1989). Tetrodotoxin-producing bacteria from the blue-ringed octopus *Octopus maculosus*. *Marine Biology* **100**, 327–332.
- HWANG, P.-A., TSAI, Y.-H., LIN, H.-P. & HWANG, D.-F. (2007). Tetrodotoxin-binding proteins isolated from five species of toxic gastropods. *Food Chemistry* **103**, 1153–1158.
- ISELL, L. A. (2009). *The Fruit, the Tree, and the Serpent*. Harvard University Press, Cambridge, MA.
- JANSA, S. A. & VOSS, R. S. (2011). Adaptive evolution of the venom-targeted vWF protein in opossums that eat pitvipers. *PLoS One* **6**, 1–9.
- JOHNSTON, D. S. & FENTON, M. B. (2001). Individual and population-level variability in diets of pallid bats (*Antrozous pallidus*). *Journal of Mammalogy* **82**, 362–373.
- JOLLEY, D. B., DITCHKOFF, S. S., SPARKLIN, B. D., HANSON, L. B., MITCHELL, M. S. & GRAND, J. B. (2010). Estimate of herpetofauna depredation by a population of wild pigs. *Journal of Mammalogy* **91**, 519–524.
- JOLLY, C. J., SHINE, R. & GREENLEES, M. J. (2015). The impact of invasive cane toads on native wildlife in southern Australia. *Ecology and Evolution* **5**, 3879–3894.
- JONES, M. D., CRANE, M. S., SILVA, I. M. S., ARTCHAWAKOM, T., WAENGSOOTHORN, S., SUWANWAREE, P., STRINE, C. T. & GOODE, M. (2020). Supposed snake specialist consumes monitor lizards: diet and trophic implications of king cobra feeding ecology. *Ecology* **101**, 1–4.
- JONES, L., HARRIS, R. J. & FRY, B. G. (2021). Not goanna get me: mutations in the savannah monitor lizard (*Varanus exanthematicus*) nicotinic acetylcholine receptor confer reduced susceptibility to sympatric cobra venoms. *Neurotoxicity Research* **39**, 1116–1122.
- JOST, M. C., HILLIS, D. M., LU, Y., KYLE, J. W., FOZZARD, H. A. & ZAKON, H. H. (2008). Toxin-resistant sodium channels: parallel adaptive evolution across a complete gene family. *Molecular Biology and Evolution* **25**, 1016–1024.
- *JURGLAS, P. B., NEVES-FERREIRA, A. G., DOMONT, G. B. & PERALES, J. (2003). PO41, a snake venom metalloproteinase inhibitor isolated from philander opossum serum. *Toxicon* **42**, 621–628.
- KACHALSKY, S. G., JENSEN, B. S., BARCHAN, D. & FUCHS, S. (1995). Two subsites in the binding domain of the acetylcholine receptor: an aromatic subsite and a proline subsite. *Proceedings of the National Academy of Sciences of the United States of America* **92**, 10801–10805.
- KARAGEORGI, M., GROEN, S. C., SUMBUL, F., PELAEZ, J. N., VERSTER, K. I., AGUILAR, J. M., HASTINGS, A. P., BERNSTEIN, S. L., MATSUNAGA, T., ASTOURIAN, M., GUERRA, G., RICO, F., DOBLER, S., AGRAWAL, A. A. & WHITEMAN, N. K. (2019). Genome editing retraces the evolution of toxin resistance in the monarch butterfly. *Nature* **574**, 409–412.
- KAZANJIAN, T. D., PETRAS, D., ROBINSON, S. D., VAN THIEL, J., GREENE, H. W., ARBUCKLE, K., BARLOW, A., CARTER, D. A., WOUTERS, R. M., WHITELEY, G., WAGSTAFF, S. C., ARIAS, A. S., ALBULESCU, L. O., PLETTENBERG LAING, A., HALL, C., HEAP, A., et al. (2021). Convergent evolution of pain-inducing defensive venom components in spitting cobras. *Science* **371**, 386–390.

- KGADITSE, M. M. (2016). *The evolution and diversification of diet in elapids*. Doctoral dissertation: University of the Witwatersrand.
- KHAN, M. A., DASHEVSKY, D., KERKAMP, H., KORDIS, D., DE BAKKER, M. A. G., WOUTERS, R., VAN THIEL, J., OP DEN BROUW, B., VONK, F., KINI, R. M., NAZIR, J., FRY, B. G. & RICHARDSON, M. K. (2020). Widespread evolution of molecular resistance to snake venom alpha-neurotoxins in vertebrates. *Toxins* **12**, 1–20.
- KINI, R. M. (2019). Toxins for decoding interface selectivity in nicotinic acetylcholine receptors. *Biochemical Journal* **476**, 1515–1520.
- KODAMA, M., OGATA, T. & SATO, S. (1985). External secretion of tetrodotoxin from puffer fishes stimulated by electric shock. *Marine Biology* **87**, 199–202.
- *KOGAKI, H., INOUE, S., IKEDA, K., SAMEJIMA, Y., OMORI-SATOH, T. & HAMAGUCHI, K. (1989). Isolation and fundamental properties of a phospholipase A₂ inhibitor from the blood plasma of *Trimeresurus flavoviridis*. *The Journal of Biochemistry* **106**, 966–971.
- KUMAR, S., STECHER, G., SULESKI, M. & HEDGES, S. B. (2017). TimeTree: a resource for timelines, timetrees, and divergence times. *Molecular Biology and Evolution* **34**, 1812–1819.
- LAYLOO, I., SMITH, C. & MARITZ, B. (2017). Diet and feeding in the cape cobra, *Naja nivea*. *African Journal of Herpetology* **66**, 147–153.
- LEE, C. H., JONES, D. K., AHERN, C., SARHAN, M. F. & RUBEN, P. C. (2011). Biophysical costs associated with tetrodotoxin resistance in the sodium channel pore of the garter snake, *Thamnophis sirtalis*. *Journal of Comparative Physiology A* **197**, 33–43.
- LENHART, P. A., MATA-SILVA, V. & JOHNSON, J. D. (2010). Foods of the pallid bat, *Antrozous pallidus* (Chiroptera: Vespertilionidae), in the Chihuahuan Desert of Western Texas. *The Southwestern Naturalist* **55**, 110–115.
- LIN, H., ZHANG, C., LIAO, J., YANG, F., ZHONG, S., JIANG, P., CHEN, X. & NAGASHIMA, Y. (2015). Neutralizing effect of hemolymph from the shore crab, *Thalamita crenata*, on paralytic shellfish toxins. *Toxicon* **99**, 51–57.
- *LIZANO, S., LOMONTE, B., FOX, J. W. & GUTIÉRREZ, J. M. (1997). Biochemical characterization and pharmacological properties of a phospholipase A₂ myotoxin inhibitor from the plasma of the snake *Bothrops asper*. *The Biochemical Journal* **326**, 853–859.
- *LIZANO, S., ANGULO, Y., LOMONTE, B., FOX, J. W., LAMBEAU, G., LAZDUNSKI, M. & GUTIÉRREZ, J. M. (2000). Two phospholipase A₂ inhibitors from the plasma of *Cerrophidion (Bothrops) godmani* which selectively inhibit two different group-II phospholipase A₂ myotoxins from its own venom: isolation, molecular cloning and biological properties. *The Biochemical Journal* **346**, 631–639.
- LIZANO, S., DOMONT, G. & PERALES, J. (2003). Natural phospholipase A₂ myotoxin inhibitor proteins from snakes, mammals and plants. *Toxicon* **42**, 963–977.
- LLEWELYN, L. E., BELL, P. M. & MOCZYDŁOWSKI, E. G. (1997). Phylogenetic survey of soluble saxitoxin-binding activity in pursuit of the function and molecular evolution of saxiphilin, a relative of transferrin. *Proceedings of the Royal Society of London. Series B: Biological Sciences* **264**, 891–902.
- LUCAS, A. & STETTENHEIM, P. (1972). *Avian Anatomy-Integument*. US Department of Agriculture Handbook, Washington, DC.
- MACKESSY, S. P. & BAXTER, L. M. (2006). Bioweapons synthesis and storage: the venom gland of front-fanged snakes. *Zoologischer Anzeiger—A Journal of Comparative Zoology* **245**, 147–159.
- MAJSEN, T. & UJVARI, B. (2009). Increased mortality of naive varanid lizards after the invasion of non-native cane toads (*Bufo marinus*). *Herpetological Conservation and Biology* **4**, 248–251.
- MAHAR, J., LUKÁCS, G. L., LI, L., HALL, S. & MOCZYDŁOWSKI, E. (1991). Pharmacological and biochemical properties of saxiphilin, a soluble saxitoxin-binding protein from the bullfrog (*Rana catesbeiana*). *Toxicon* **29**, 53–71.
- MANJUNATHA KINI, R. (2003). Excitement ahead: structure, function and mechanism of snake venom phospholipase A₂ enzymes. *Toxicon* **42**, 827–840.
- MARGRES, M. J., WRAY, K. P., HASSINGER, A. T. B., WARD, M. J., MCGIVERN, J. J., MORIARTY LEMMON, E., LEMMON, A. R. & ROKYTA, D. R. (2017). Quantity, not quality: rapid adaptation in a polygenic trait proceeded exclusively through expression differentiation. *Molecular Biology and Evolution* **34**, 3099–3110.
- MARITZ, B., ALEXANDER, G. J. & MARITZ, R. A. (2019). The underappreciated extent of cannibalism and ophiophagy in African cobras. *Ecology* **100**, 1–4.
- MARQUES, O. A. V., MARTINS, M., DEVELEY, P. F., MACARRAO, A. & SAZIMA, I. (2012). The golden lancehead *Bothrops insularis* (Serpentes: Viperidae) relies on two seasonally plentiful bird species visiting its Island habitat. *Journal of Natural History* **46**, 885–895.
- MARTINEZ, R. R., PÉREZ, J. C., SÁNCHEZ, E. E. & CAMPOS, R. (1999). The antihemorrhagic factor of the Mexican ground squirrel (*Spermophilus mexicanus*). *Toxicon* **37**, 949–954.
- MARTINS, M. & ERMELINDA OLIVEIRA, M. (1998). Natural history of snakes in forests of the Manaus region, Central Amazonia, Brazil. *Herpetological Natural History* **6**, 78–150.
- MCGLOTHLIN, J. W., CHUCKALOVCAK, J. P., JANES, D. E., EDWARDS, S. V., FELDMAN, C. R., BRODIE, E. D. JR., PFRENDER, M. E. & BRODIE, E. D. III (2014). Parallel evolution of tetrodotoxin resistance in three voltage-gated sodium channel genes in the garter snake *Thamnophis sirtalis*. *Molecular Biology and Evolution* **31**, 2836–2846.
- MCGLOTHLIN, J. W., KOBIELA, M. E., FELDMAN, C. R., CASTOE, T. A., GEFFENEY, S. L., HANIFIN, C. T., TOLEDO, G., VONK, F. J., RICHARDSON, M. K., BRODIE, E. D. JR., PFRENDER, M. E. & BRODIE, E. D. III (2016). Historical contingency in a multigene family facilitates adaptive evolution of toxin resistance. *Current Biology* **26**, 1616–1621.
- MEBS, D., OMORI-SATOH, T., YAMAKAWA, Y. & NAGAOKA, Y. (1996). Erinacin, an antihemorrhagic factor from the European hedgehog, *Erinaceus europaeus*. *Toxicon* **34**, 1313–1316.
- MIYAZAWA, K. & NOGUCHI, T. (2001). Distribution and origin of tetrodotoxin. *Journal of Toxicology: Toxin Reviews* **20**, 11–33.
- MODAHL, C. M. & MACKESSY, S. P. (2019). Venoms of rear-fanged snakes: new proteins and novel activities. *Frontiers in Ecology and Evolution* **7**, 1–18.
- MOHAMMADI, S., GOMPERT, Z., GONZALEZ, J., TAKEUCHI, H., MORI, A. & SAVITZKY, A. H. (2016). Toxin-resistant isoforms of Na⁺/K⁺-ATPase in snakes do not closely track dietary specialization on toads. *Proceedings of the Royal Society B: Biological Sciences* **283**, 1–9.
- MOHAMMADI, S., PETSCHENKA, G., FRENCH, S. S., MORI, A. & SAVITZKY, A. H. (2018). Snakes exhibit tissue-specific variation in cardiotonic steroid sensitivity of Na⁺/K⁺-ATPase. *Comparative Biochemistry and Physiology Part B: Biochemistry and Molecular Biology* **217**, 21–26.
- MOHAMMADI, S., YANG, L., HARPAK, A., HERRERA-ÁLVAREZ, S., DEL PILAR RODRÍGUEZ-ORDOÑEZ, M., PENG, J., ZHANG, K., STORZ, J. F., DOBLER, S., CRAWFORD, A. J. & ANDOLFATTO, P. (2021). Concerted evolution reveals co-adapted amino acid substitutions in Na⁺K⁺-ATPase of frogs that prey on toxic toads. *Current Biology* **31**, 2530–2538.
- MOORE, D. J., HALLIDAY, D. C., ROWELL, D. M., ROBINSON, A. J. & KEOGH, J. S. (2009). Positive Darwinian selection results in resistance to cardioactive toxins in true toads (Anura: Bufonidae). *Biology Letters* **5**, 513–516.
- MORI, A., BURGHARDT, G. M., SAVITZKY, A. H., ROBERTS, K. A., HUTCHINSON, D. A. & GORIS, R. C. (2012). Nuchal glands: a novel defensive system in snakes. *Chemoecology* **22**, 187–198.
- MORI, D., VYAS, R. & UPADHYAY, K. (2017). Breeding biology of the short-toed Snake Eagle *Circus galliae*. *Indian Birds* **12**, 149–156.
- MUNEKIYO, S. M. & MACKESSY, S. P. (2005). Presence of peptide inhibitors in rattlesnake venoms and their effects on endogenous metalloproteases. *Toxicon* **45**, 255–263.
- *NEVES-FERREIRA, A. G., PERALES, J., FOX, J. W., SHANNON, J. D., MAKINO, D. L., GARRATT, R. C. & DOMONT, G. B. (2002). Structural and functional analyses of DM43, a snake venom metalloproteinase inhibitor from *Didelphis marsupialis* serum. *Journal of Biological Chemistry* **277**, 13129–13137.
- NOGUCHI, T., ARAKAWA, O. & TAKATANI, T. (2006a). Toxicity of pufferfish *Takifugu rubripes* cultured in netcages at sea or aquaria on land. *Comparative Biochemistry and Physiology Part D: Genomics and Proteomics* **1**, 153–157.
- NOGUCHI, T., ARAKAWA, O. & TAKATANI, T. (2006b). TTX accumulation in pufferfish. *Comparative Biochemistry and Physiology Part D: Genomics and Proteomics* **1**, 145–152.
- O'CONNELL, L. A., LS50: INTEGRATED SCIENCE LABORATORY COURSE, O'CONNELL, J. D., PAULO, J. A., TRAUGER, S. A., GYGI, S. P. & MURRAY, A. W. (2021). Rapid toxin sequestration modifies poison frog physiology. *Journal of Experimental Biology* **224**, 1–8.
- *OHKURA, N., INOUE, S., IKEDA, K. & HAYASHI, K. (1994). Isolation and characterization of a phospholipase A₂ inhibitor from the blood plasma of the Thailand cobra *Naja naja kaouthia*. *Biochemical and Biophysical Research Communications* **200**, 784–788.
- *OHKURA, N., OKUHARA, H., INOUE, S., IKEDA, K. & HAYASHI, K. (1997). Purification and characterization of three distinct types of phospholipase A₂ inhibitors from the blood plasma of the Chinese mamushi, *Agkistrodon blomhoffii siniticus*. *The Biochemical Journal* **325**, 527–531.
- *OHKURA, N., KITAHARA, Y., INOUE, S., IKEDA, K. & HAYASHI, K. (1999). Isolation and amino acid sequence of a phospholipase A₂ inhibitor from the blood plasma of the sea krait, *Laticauda semifasciata*. *The Journal of Biochemistry* **125**, 375–382.
- OLIVEIRA, M. E. & SANTORI, R. T. (1999). Predatory behavior of the opossum *Didelphis albiventris* on the pitviper *Bothrops jararaca*. *Studies on Neotropical Fauna and Environment* **34**, 72–75.
- *OMORI-SATOH, T., SADAHIRO, S., OHSAKA, A. & MURATA, R. (1972). Purification and characterization of an antihemorrhagic factor in the serum of *Trimeresurus flavoviridis*, a crotalid. *Biochimica et Biophysica Acta* **285**, 414–426.
- OMORI-SATOH, T., YAMAKAWA, Y. & MEBS, D. (2000). The antihemorrhagic factor, erinacin, from the European hedgehog (*Erinaceus europaeus*), a metalloprotease inhibitor of large molecular size possessing ficolin/opsonin P35 lectin domains. *Toxicon* **38**, 1561–1580.
- *OVADIA, M. (1978). Purification and characterization of an antihemorrhagic factor from the serum of the snake *Vipera palaestinae*. *Toxicon* **16**, 661–672.

- *PERALES, J., MUNOZ, R. & MOUSSATCHÉ, H. (1986). Isolation and partial characterization of a protein fraction from the opossum (*Didelphis marsupialis*) serum, with protecting property against the *Bothrops jararaca* snake venom. *Anais da Academia Brasileira de Ciências* **58**, 155–162.
- PERALES, J., MOUSSATCHE, H., MARANGONI, S., OLIVEIRA, B. & DOMONT, G. B. (1994). Isolation and partial characterization of an anti-bothropic complex from the serum of South American Didelphidae. *Toxicon* **32**, 1237–1249.
- PERALES, J., VILLELA, C., DOMONT, G. B., CHOUMET, V., SALIOU, B., MOUSSATCHÉ, H., BON, C. & FAURE, G. (1995). Molecular structure and mechanism of action of the crotoxin inhibitor from *Crotalus durissus terrificus* serum. *European Journal of Biochemistry* **227**, 19–26.
- PEREZ, J. C., PICHYANGKUL, S. & GARCIA, V. E. (1979). The resistance of three species of warm-blooded animals to western diamondback rattlesnake (*Crotalus atrox*) venom. *Toxicon* **17**, 601–607.
- PHILLIPS, J. M., BRICELJ, V. M., MITCH, M., CERRATO, R. M., MACQUARRIE, S. & CONNELL, L. B. (2018). Biogeography of resistance to paralytic shellfish toxins in softshell clam, *Mya arenaria* (L.), populations along the Atlantic coast of North America. *Aquatic Toxicology* **202**, 196–206.
- PICHYANGKUL, S. & PEREZ, J. C. (1981). Purification and characterization of a naturally occurring antihemorrhagic factor in the serum of the hispid cotton rat (*Sigmodon hispidus*). *Toxicon* **19**, 205–215.
- POMENTO, A. M., PERRY, B. W., DENTON, R. D., GIBBS, H. L. & HOLDING, M. L. (2016). No safety in the trees: local and species-level adaptation of an arboreal squirrel to the venom of sympatric rattlesnakes. *Toxicon* **118**, 149–155.
- PORAN, N. S., COSS, R. G. & BENJAMINI, E. (1987). Resistance of California ground squirrels (*Spermophilus beecheyi*) to the venom of the northern Pacific rattlesnake (*Crotalus viridis oreganus*): a study of adaptive variation. *Toxicon* **25**, 767–777.
- PORTUGAL, S. J., MURN, C. P., SPARKES, E. L. & DALEY, M. A. (2016). The fast and furious kicking strike of the secretary bird. *Current Biology* **26**, 58–59.
- POTIER, S., LIEUVIN, M., PFAFF, M. & KELBER, A. (2020). How fast can raptors see? *Journal of Experimental Biology* **223**, 1–7.
- *QI, Z.-Q., YONAH, K., TOMIHARA, Y. & TOYAMA, S. (1995). Isolation of peptides homologous to domains of human α 1B-glycoprotein from a mongoose antihemorrhagic factor. *Toxicon* **33**, 241–245.
- RAHMAN, M. M., TENG, J., WORRELL, B. T., NOVIELLO, C. M., LEE, M., KARLIN, A., STOWELL, M. H. B. & HIBBS, R. E. (2020). Structure of the native muscle-type nicotinic receptor and inhibition by snake venom toxins. *Neuron* **106**, 952–962.
- RAWLINGS, N. D. & BARRETT, A. J. (1990). Evolution of proteins of the cystatin superfamily. *Journal of Molecular Evolution* **30**, 60–71.
- REDFORD, K. H. & PETERS, G. (1986). Notes on the biology and song of the red-legged seriema (*Cariama cristata*). *Journal of Field Ornithology* **57**, 261–269.
- REEVE, N. (1994). *Hedgehogs*. T. & A.D. Poyser, London.
- ROCHA, S. L., LOMONTE, B., NEVES-FERREIRA, A. G., TRUGILHO, M. R., JUNQUEIRA-DE-AZEVEDO, I. L., HO, P. L., DOMONT, G. B., GUTIERREZ, J. M. & PERALES, J. (2002). Functional analysis of DM64, an antimyotoxic protein with immunoglobulin-like structure from *Didelphis marsupialis* serum. *European Journal of Biochemistry* **269**, 6052–6062.
- RODRIGUES, C. F. B., SERINO-SILVA, C., MORAIS-ZANI, K. D., KAVAZOI, V. K., CARVALHO, M. P. N., GREGO, K. F., CHIARELLI, T., TASHIMA, A. K., TOYAMA, M. H. & TANAKA-AZEVEDO, A. M. (2020). BoagPLI: structural and functional characterization of the gamma phospholipase A₂ plasma inhibitor from the non-venomous Brazilian snake *boa constrictor*. *PLoS One* **15**, 1–13.
- RODRIGUES, C. F. B., ZDENEK, C. N., SERINO-SILVA, C., DE MORAIS-ZANI, K., GREGO, K. F., BÉNARD-VALLE, M., NERI-CASTRO, E., ALAGÓN, A., TANAKA-AZEVEDO, A. M. & FRY, B. G. (2021). BoagPLI from *boa constrictor* blood is a broad-spectrum inhibitor of venom PLA₂ pathophysiological actions. *Journal of Chemical Ecology* **47**, 907–914.
- ROWE, A. H. & ROWE, M. P. (2008). Physiological resistance of grasshopper mice (*Onychomys* spp.) to Arizona bark scorpion (*Centruroides exilicauda*) venom. *Toxicon* **52**, 597–605.
- ROWE, A. H., XIAO, Y., SCALES, J., LINSE, K. D., ROWE, M. P., CUMMINS, T. R. & ZAKON, H. H. (2011). Isolation and characterization of CvIV4: a pain inducing alpha-scorpion toxin. *PLoS One* **6**, 1–13.
- ROWE, A. H., XIAO, Y., ROWE, M. P., CUMMINS, T. R. & ZAKON, H. H. (2013). Voltage-gated sodium channel in grasshopper mice defends against bark scorpion toxin. *Science* **342**, 441–446.
- SANTOS, J. C., TARVIN, R. D. & O'CONNELL, L. A. (2016). A review of chemical defense in poison frogs (Dendrobatidae): ecology, pharmacokinetics, and autoresistance. In *Chemical Signals in Vertebrates 13* (eds B. A. SCHULTE, T. E. GOODWIN and M. H. FERKIN), pp. 305–337. Springer International Publishing, Cham.
- SAPORITO, R. A., DONNELLY, M. A., JAIN, P., MARTIN GARRAFFO, H., SPANDE, T. F. & DALY, J. W. (2007a). Spatial and temporal patterns of alkaloid variation in the poison frog *Oophaga pumilio* in Costa Rica and Panama over 30 years. *Toxicon* **50**, 757–778.
- SAPORITO, R. A., DONNELLY, M. A., NORTON, R. A., GARRAFFO, H. M., SPANDE, T. F. & DALY, J. W. (2007b). Oribatid mites as a major dietary source for alkaloids in poison frogs. *Proceedings of the National Academy of Sciences of the United States of America* **104**, 8885–8890.
- SAPORITO, R. A., DONNELLY, M. A., SPANDE, T. F. & GARRAFFO, H. M. (2012). A review of chemical ecology in poison frogs. *Chemoecology* **22**, 159–168.
- SAVITZKY, A. H., MORI, A., HUTCHINSON, D. A., SAPORITO, R. A., BURGHARDT, G. M., LILLYWHITE, H. B. & MEINWALD, J. (2012). Sequestered defensive toxins in tetrapod vertebrates: principles, patterns, and prospects for future studies. *Chemoecology* **22**, 141–158.
- SCHENDEL, V., RASH, L. D., JENNER, R. A. & UNDHEIM, E. A. B. (2019). The diversity of venom: the importance of behavior and venom system morphology in understanding its ecology and evolution. *Toxins* **11**, 1–22.
- SCHONER, W. (2002). Endogenous cardiac glycosides, a new class of steroid hormones. *European Journal of Biochemistry* **269**, 2440–2448.
- SHEN, H., ZHOU, Q., PAN, X., LI, Z., WU, J. & YAN, N. (2017). Structure of a eukaryotic voltage-gated sodium channel at near-atomic resolution. *Science* **355**, 1–12.
- SHEUMACK, D. D., HOWDEN, M. E., SPENCE, I. & QUINN, R. J. (1978). Maculotoxin: a neurotoxin from the venom glands of the octopus *Hapalochloa maculosa* identified as tetrodotoxin. *Science* **199**, 188–189.
- SHINE, R. (1991). *Australian Snakes: A Natural History*. Reed, Sydney.
- SHINE, R., BRANCH, W. R., WEBB, J. K., HARLOW, P. S., SHINE, T. & KEOGH, J. S. (2007). Ecology of cobras from Southern Africa. *Journal of Zoology* **272**, 183–193.
- *SHIOI, N., DESHIMARU, M. & TERADA, S. (2014). Structural analysis and characterization of new small serum proteins from the serum of a venomous snake (*Gloydus blomhoffii*). *Bioscience, Biotechnology, and Biochemistry* **78**, 410–419.
- SILVA, A. N., NUNES, R., ESTRELA, D. C., MALAFAIA, G. & CASTRO, A. L. S. (2016). Behavioral repertoire of the poorly known red-legged seriema, *Cariama cristata* (Cariamiformes: Cariamidae). *Revista Brasileira de Ornithologia* **24**, 73–79.
- SMITH, S. M. (1977). Coral-snake pattern recognition and stimulus generalisation by naive great kiskadees (Aves: Tyrannidae). *Nature* **265**, 535–536.
- SMITH, S. N., JONES, M. D., MARSHALL, B. M., WAENGSOOTHORN, S., GALE, G. A. & STRINE, C. T. (2021). Native Burmese pythons exhibit site fidelity and preference for aquatic habitats in an agricultural mosaic. *Scientific Reports* **11**, 1–13.
- SOARES, A. M., RODRIGUES, V. M., BORGES, M. H., ANDRAIO-ESCARSO, S. H., CUNHA, O. A., HOMSI-BRANDEBURGO, M. I. & GIGLIO, J. R. (1997). Inhibition of proteases, myotoxins and phospholipases A₂ from *Bothrops* venoms by the heteromeric protein complex of *Didelphis albiventris* opossum serum. *IUBMB Life* **43**, 1091–1099.
- *SOARES, A. M., MARCUSSI, S., STÁBELI, R. G., FRANÇA, S. C., GIGLIO, J. R., WARD, R. J. & ARANTES, E. C. (2003). Structural and functional analysis of BmjMIP, a phospholipase A₂ myotoxin inhibitor protein from *Bothrops moojeni* snake plasma. *Biochemical and Biophysical Research Communications* **302**, 193–200.
- SOONG, T. W. & VENKATESH, B. (2006). Adaptive evolution of tetrodotoxin resistance in animals. *Trends in Genetics* **22**, 621–626.
- STORZ, J. F. (2016). Causes of molecular convergence and parallelism in protein evolution. *Nature Reviews Genetics* **17**, 239–250.
- STRUHSAKER, T. T. & MCKEY, D. (1975). Two cusimanse mongooses attack a black cobra. *Journal of Mammalogy* **56**, 721–722.
- STUART, C. T. (1983). Food of the large grey mongoose *Herpestes ichneumon* in the south-west Cape Province. *South African Journal of Zoology* **18**, 401–403.
- SUMMERS, K. & CLOUGH, M. E. (2001). The evolution of coloration and toxicity in the poison frog family (Dendrobatidae). *Proceedings of the National Academy of Sciences of the United States of America* **98**, 6227–6232.
- TAKACS, Z., WILHELMSSEN, K. C. & SOROTA, S. (2001). Snake α -neurotoxin binding site on the Egyptian cobra (*Naja haje*) nicotinic acetylcholine receptor is conserved. *Molecular Biology and Evolution* **18**, 1800–1809.
- TAKACS, Z., WILHELMSSEN, K. C. & SOROTA, S. (2004). Cobra (*Naja* spp.) nicotinic acetylcholine receptor exhibits resistance to Erabu Sea snake (*Laticauda semifasciata*) short-chain alpha-neurotoxin. *Journal of Molecular Evolution* **58**, 516–526.
- TAKATI, N., MOUNTASSIF, D., TALEB, H., LEE, K. & BLAGHEN, M. (2007). Purification and partial characterization of paralytic shellfish poison-binding protein from *Acanthocardia tuberculatum*. *Toxicon* **50**, 311–321.
- TANAKA, K. & MORI, A. (2000). Literature survey on predators of snakes in Japan. *Current Herpetology* **19**, 97–111.
- *TANIZAKI, M. M., KAWASAKI, H., SUZUKI, K. & MANDELBAUM, F. R. (1991). Purification of a proteinase inhibitor from the plasma of *Bothrops jararaca* (jararaca). *Toxicon* **29**, 673–681.
- TARVIN, R. D., SANTOS, J. C., O'CONNELL, L. A., ZAKON, H. H. & CANNATELLA, D. C. (2016). Convergent substitutions in a sodium channel suggest multiple origins of toxin resistance in poison frogs. *Molecular Biology and Evolution* **33**, 1068–1080.
- TARVIN, R. D., BORGHESE, C. M., SACHS, W., SANTOS, J. C., LU, Y., O'CONNELL, L. A., CANNATELLA, D. C., HARRIS, R. A. & ZAKON, H. H. (2017). Interacting amino acid replacements allow poison frogs to evolve epibatidine resistance. *Science* **357**, 1261–1266.
- TASOULIS, T. & ISBISTER, G. K. (2017). A review and database of snake venom proteomes. *Toxins* **9**, 1–23.

- THWIN, M. M., GOPALAKRISHNAKONE, P., KINI, R. M., ARMUGAM, A. & JEVASEELAN, K. (2000). Recombinant antitoxic and antiinflammatory factor from the nonvenomous snake *Python reticulatus*: phospholipase A₂ inhibition and venom neutralizing potential. *Biochemistry* **39**, 9604–9611.
- *TOMIHARA, Y., YONAHARA, K., NOZAKI, M., YAMAKAWA, M., KAMURA, T. & TOYAMA, S. (1987). Purification of three antihemorrhagic factors from the serum of a mongoose (*Herpestes edwardsii*). *Toxicon* **25**, 685–689.
- TOMIHARA, Y., YONAHARA, K., NOZAKI, M., YAMAKAWA, M., KAWAMURA, Y., KAMURA, T. & TOYAMA, S. (1988). Purification of an antihemorrhagic factor from the serum of the non-venomous snake *Dinodon semicarinatus*. *Toxicon* **26**, 420–423.
- UJVARI, B., MUN, H. C., CONIGRAVE, A. D., BRAY, A., OSTERKAMP, J., HALLING, P. & MADSEN, T. (2013). Isolation breeds naivety: Island living robs Australian varanid lizards of toad-toxin immunity via four-base-pair mutation. *Evolution* **67**, 289–294.
- UJVARI, B., CASEWELL, N. R., SUNAGAR, K., ARBUCKLE, K., WÜSTER, W., LO, N., O'MEALLY, D., BECKMANN, C., KING, G. F., DEPLAZES, E. & MADSEN, T. (2015). Widespread convergence in toxin resistance by predictable molecular evolution. *Proceedings of the National Academy of Sciences of the United States of America* **112**, 11911–11916.
- VAELLI, P. M., THEIS, K. R., WILLIAMS, J. E., O'CONNELL, L. A., FOSTER, J. A. & EISTHEN, H. L. (2020). The skin microbiome facilitates adaptive tetrodotoxin production in poisonous newts. *Life* **9**, 1–29.
- VALENTE, R. H., DRAGULEV, B., PERALES, J., FOX, J. W. & DOMONT, G. B. (2001). BJ46a, a snake venom metalloproteinase inhibitor. Isolation, characterization, cloning and insights into its mechanism of action. *European Journal of Biochemistry* **268**, 3042–3052.
- VALENTE, R. H., LUNA, M. S., DE OLIVEIRA, U. C., NISHIYAMA-JUNIOR, M. Y., JUNQUEIRA-DE-AZEVEDO, I. L., PORTES-JUNIOR, J. A., CLISSA, P. B., VIANA, L. G., SANCHES, L., MOURA-DA-SILVA, A. M., PERALES, J. & YAMANOUYE, N. (2018). *Bothrops jararaca* accessory venom gland is an ancillary source of toxins to the snake. *Journal of Proteomics* **177**, 137–147.
- VENKATESH, B., LU, S. Q., DANDONA, N., SEE, S. L., BRENNER, S. & SOONG, T. W. (2005). Genetic basis of tetrodotoxin resistance in pufferfishes. *Current Biology* **15**, 2069–2072.
- VOSS, R. S. (2013). Opossums (Mammalia: Didelphidae) in the diets of Neotropical pitvipers (Serpentes: Crotalinae): evidence for alternative coevolutionary outcomes? *Toxicon* **66**, 1–6.
- WALKER, A. A., ROBINSON, S. D., PALUZZI, J.-P. V., MERRITT, D. J., NIXON, S. A., SCHROEDER, C. I., JIN, J., GOUDARZI, M. H., KOTZE, A. C., DEKAN, Z., SOMBEKE, A., ALEWOOD, P. F., FRY, B. G., EPSTEIN, M. E., VETTER, I. & KING, G. F. (2021). Production, composition, and mode of action of the painful defensive venom produced by a limacodid caterpillar, *Doratifera vulnerans*. *Proceedings of the National Academy of Sciences of the United States of America* **118**, 1–12.
- WANG, S.-Y. & WANG, G. K. (2017). Single rat muscle Na⁺ channel mutation confers batrachotoxin autoresistance found in poison-dart frog *Phylllobates terribilis*. *Proceedings of the National Academy of Sciences of the United States of America* **114**, 10491–10496.
- WERNER, R. M. & VICK, J. A. (1977). Resistance of the opossum (*Didelphis virginiana*) to envenomation by snakes of the family Crotalidae. *Toxicon* **15**, 29–32.
- WHITELAW, B. L., COOKE, I. R., FINN, J., DA FONSECA, R. R., RITSCHARD, E. A., GILBERT, M. T. P., SIMAKOV, O. & STRUGNELL, J. M. (2020). Adaptive venom evolution and toxicity in octopods is driven by extensive novel gene formation, expansion, and loss. *Gigascience* **9**, 1–15.
- WHITFORD, M. D., FREYMLER, G. A., HIGHAM, T. E. & CLARK, R. W. (2019). Determinants of predation success: how to survive an attack from a rattlesnake. *Functional Ecology* **33**, 1099–1109.
- WILCOX, J. (2015). Implications of predation by wild pigs on native vertebrates: a case study. *California Fish and Game* **101**, 72–77.
- WILLIAMS, B. L. & CALDWELL, R. L. (2009). Intra-organismal distribution of tetrodotoxin in two species of blue-ringed octopuses (*Haplochroma fasciata* and *H. lunulata*). *Toxicon* **54**, 345–353.
- WILLIAMS, B. L., BRODIE, E. D. & BRODIE, E. D. (2004). A resistant predator and its toxic prey: persistence of newt toxin leads to poisonous (not venomous) snakes. *Journal of Chemical Ecology* **30**, 1901–1919.
- DE WIT, C. A. (1982). Resistance of the prairie vole (*Microtus ochrogaster*) and the woodrat (*Neotoma floridana*), in Kansas, to venom of the Osage copperhead (*Agkistrodon contortrix phaeogaster*). *Toxicon* **20**, 709–714.
- *DE WIT, C. A. & WESTROM, B. R. (1987). Venom resistance in the hedgehog, *Eriacus europaeus*: purification and identification of macroglobulin inhibitors as plasma antihemorrhagic factors. *Toxicon* **25**, 315–323.
- YAMAGUCHI, Y., PARK, J. H. & INOUE, M. (2011). Toxin-antitoxin systems in bacteria and archaea. *Annual Review of Genetics* **45**, 61–79.
- YEE, K. T., PITTS, M., TONGYOO, P., ROJNUCKARIN, P. & WILKINSON, M. C. (2016). Snake venom metalloproteinases and their peptide inhibitors from Myanmar russell's viper venom. *Toxins* **9**, 1–20.
- YEN, T.-J., LOLICATO, M., THOMAS-TRAN, R., BOIS, J. D. & MINOR, D. L. (2019). Structure of the saxiphilin:saxitoxin (STX) complex reveals a convergent molecular recognition strategy for paralytic toxins. *Science Advances* **5**, 1–10.
- YOTSU-YAMASHITA, M., NISHIMORI, K., NITANAI, Y., ISEMURA, M., SUGIMOTO, A. & YASUMOTO, T. (2000). Binding properties of (3)H-PbTx-3 and (3)H-saxitoxin to brain membranes and to skeletal muscle membranes of puffer fish *Fugu pardalis* and the primary structure of a voltage-gated Na⁺ channel alpha-subunit (fMNa1) from skeletal muscle of *F. pardalis*. *Biochemical and Biophysical Research Communications* **267**, 403–412.
- YOTSU-YAMASHITA, M., MEBS, D. & FLACHSENBERGER, W. (2007). Distribution of tetrodotoxin in the body of the blue-ringed octopus (*Haplochroma maculosa*). *Toxicon* **49**, 410–412.
- YOTSU-YAMASHITA, M., YAMAKI, H., OKOSHI, N. & ARAKI, N. (2010). Distribution of homologous proteins to puffer fish saxitoxin and tetrodotoxin binding protein in the plasma of puffer fish and among the tissues of *Fugu pardalis* examined by western blot analysis. *Toxicon* **55**, 1119–1124.
- YOTSU-YAMASHITA, M., GILHEN, J., RUSSELL, R. W., KRYSKO, K. L., MELAUN, C., KURZ, A., KAUFERSTEIN, S., KORDIS, D. & MEBS, D. (2012). Variability of tetrodotoxin and of its analogues in the red-spotted newt, *Notophthalmus viridescens* (Amphibia: Urodela: Salamandridae). *Toxicon* **59**, 257–264.
- YOUNGMAN, N. J., LLINAS, J. & FRY, B. G. (2021). Evidence for resistance to coagulotoxic effects of Australian clasp snake venoms by sympatric prey (blue tongue skinks) but not by predators (monitor lizards). *Toxins* **13**, 1–11.
- ZANCOLLI, G. & CASEWELL, N. R. (2020). Venom systems as models for studying the origin and regulation of evolutionary novelties. *Molecular Biology and Evolution* **37**, 2777–2790.
- ZHEN, Y., AARDEMA, M. L., MEDINA, E. M., SCHUMER, M. & ANDOLFATTO, P. (2012). Parallel molecular evolution in an herbivore community. *Science* **337**, 1634–1637.
- ZHONG, L. & HUANG, C. (2016). Isolation and biochemical characterization of a gamma-type phospholipase A₂ inhibitor from *Macropisthodon rudis* snake serum. *Toxicon* **122**, 1–6.

VII. Supporting information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

- Table S1.** Snake venom metalloproteinase inhibitors (SVMPIs) from mammalian serum, plasma or muscle tissue.
- Table S2.** Snake venom metalloproteinase inhibitors (SVMPIs) derived from snake serum, plasma or liver tissue.
- Table S3.** Phospholipase A₂ inhibitors (PLA₂Is) from snake serum, plasma or liver.
- Table S4.** Overview of the key sites on the muscle-type nicotinic acetylcholine receptor (nAChR) and mutations that confer α-neurotoxin resistance.
- Table S5.** Accession numbers of sequences included in Fig. 2.
- Table S6.** Accession numbers of sequences included in Fig. 4.
- Table S7.** Accession numbers of sequences included in Fig. 5.
- Table S8.** Accession numbers of sequences included in Fig. 6.
- Table S9.** Accession numbers of sequences included in Fig. 7.

(Received 17 November 2021; revised 22 April 2022; accepted 26 April 2022; published online 17 May 2022)