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Artem V. Domashevskiy
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Potyviral Genome-Linked Protein and its Interaction with Plant Defense Ribosome Inactivating Protein from *Phytolacca Americana*

Artem V Domashevskiy*

Department of Sciences, John Jay College of Criminal Justice, City University of New York, New York

*Corresponding author: Artem V Domashevskiy, Department of Sciences, John Jay College of Criminal Justice, City University of New York, 524 West 59th Street, NY 10019, New York, Tel: 91 6465574640; Fax: 91 2126213739; E-mail: adomashevskiy@jjay.cuny.edu

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Abstract

Agriculture is an indispensable part of every person's life, ensuring that nutritious and inexpensive food is readily available. Agriculture continues to be confronted with epidemics, having devastating effects on economies and the plant sources essential for human and animal life. Plants and their pathogens have developed evolutionary adaptations, each shaping the other's defence and invasive strategies. Many different plants produce toxic ribosome inactivating proteins that aid in their defence mechanisms against pathogenic invaders. Viruses must adapt to the host translational machinery, several having evolved to include viral genome-linked proteins that carry numerous viral functions. Here, we review how a potyviral protein from turnip mosaic virus linked to its genome is able to inhibit pokeweed plant defence protein, and perhaps potentially conferring viral resistance to the toxin.

Introduction

For eons, plants and their pathogens have been developing and shaping survival strategies. Plant defence mechanisms include preformed and induced defences, which prevent pathogens from entering the plant cell, limit availability and/or restrict nutrients necessary for the growth and replication of the pathogen [1-3]. Essential pre-invasive defences include: physical barriers that prevent access of the pathogen, leading to the inability of most microbes to infiltrate outer epidermal wall [4]. The plant actin cytoskeleton network is another important impediment encountered upon pathogen ingress [5]. Chemical barriers, including phytoanticipins, have many roles in plant development and growth; many have evolved to affect pathogenesis. Some examples include saponin glucosinates, sterols, and glycoalkaloids [6,7].

Ribosome inactivating proteins (RIPs)

Many members of the kingdom of *Plantae* manufacture protein phytochemicals that include various lectins, pore-forming toxins, antimicrobial proteins, protease inhibitors, arcelins, and ribosome inactivating proteins (RIPs) [8]. RIPs are believed to play a vital role in plants defence mechanisms against foreign pathogenic invaders. The toxicity of several RIPs has been explored since antiquity for their homicidal capabilities, with such well-known examples as ricin (from *R. communis*) and abrin toxin (from *A. precatorius*) [9]. RIPs are RNA N-glycosidases [10] that cleave adenines selectively from the conserved sarcin/ricin loop (SRL) of prokaryotic and eukaryotic large rRNAs, inhibiting protein synthesis [11,12]. American pokeweed plant (*Phytolacca americana*) and common soapwort (*S. officinalis*) produce pokeweed antiviral protein (PAP) [13] and saporin [14], respectively; both exert potent antifungal and antiviral properties. Commonly, RIPs being potent cellular toxins are exported out of the cell once they are synthesized, and localized within the cell wall matrix [15-17]. It is hypothesized that RIPs gain access into the cytoplasm as the pathogen enters the cell, thus promoting their antiviral activity by impairing host ribosomes [18,19].

RIPs are categorized into two major classes based on their physical properties: holo-RIPs and chimeric-RIPs [20]. Holo-RIPs consist exclusively of a single RNA N-glycosidase catalytic domain. Most holo-RIPs consist of a single, intact polypeptide of approximately 30 kDa and are often referred to as type 1 RIPs [13,21,22]. Examples of holo-RIPs include PAP, saporin, and barley (*H. vulgare*) translational inhibitor. The majority of RIPs characterized thus far fall into this category [21]. Chimeric-RIPs are constructed of one or more protomers consisting of catalytic N-glycosidase domain (A chain) linked through a disulfide bond to a structurally and functionally different domain with carbohydrate binding properties (B chain). Most chimeric-RIPs are known as type 2 RIPs, like ricin and abrin, and are acutely toxic heterodimeric proteins, each of approximately 30 kDa [23,24]. The type 2 RIPs have been quite valuable for studies of endocytosis and intracellular transport in mammalian cells [16,25,26]. Some chimeric-RIPs are rather classified into type 3 class RIPs, which are much less common. Type 3 RIPs are synthesized as inert precursors (proRIPs) that undergo proteolytic modifications, allowing for acquisition of full enzymatic activity [20]. Presently, type 3 RIPs have been identified from maize (*Z. mays*) and barley [27-30].

American pokeweed plant produces several PAP isoforms [22]. PAP-I (or simply PAP), PAP-II and PAP-III are leaf isoforms that appear in spring, early summer and late summer respectively [13,22,31-35], whereas PAP-S1 and PAP-S2 are isoforms isolated from seeds that exhibit the highest activity *in vitro* of all the isoforms [36-38]. A further isoform, α -PAP, is similar in sequence to PAP-S1, and essentially expressed in all organs of the plant [38,39]; it shares 74% identity with PAP. PAP-R has been isolated from the roots of pokeweed plant [40,41] and PAP-H is from hairy roots [40]. Interesting to note that RIP-free callus and suspension cultures of *P. americana* have been acquired [40,42]. All PAP isoforms present prominent antiviral characteristics with high anti-ribosomal activity [31], and the molecular antiviral mechanism of PAP has been deciphered [43]. Examination of PAP's viral selectivity is of pivotal importance, for it lowers infectivity of many plant and animal viruses, such as HIV-1 [44], human T-cell leukemia virus-1 (HTLV-1) [45],

herpes simplex virus (HSV) [46], brome mosaic virus (BMV) [47], tobacco mosaic virus (TMV) [42], influenza [48], hepatitis B virus (HBV) [49], and poliovirus [50]. Understanding of PAP antiviral mechanism will contribute to the development of practical solutions for the control of plant, animal and human diseases, and is important for design of novel efficient antiviral agents through genetic modifications, control of signaling mechanisms, or other therapeutic agents.

Positive strand RNA viruses: the genus *potyvirus*

The majority of positive strand plant RNA viruses differ from the typical 5'-cap/3'-poly(A) tail organization found in host mRNAs. The cap and poly(A) tail increase the stability of mRNA, and recruit translation initiation factors, supporting a format of closed loop mRNA translation [51]. The assorted collection of cis-acting motifs, found in numerous viral mRNAs, compensate for the lack of a cap, poly(A) tail, or both. Elaborate higher-order structural non-coding elements in the 5' and 3' untranslated regions (UTRs), or tRNA-like structures (TLS) of viral transcripts, aid in the recruitment of translation factors, leading to the preferential translation of viral genes [52-55]. Zeenko and Gallie [54] showed the 5'-UTR of tobacco etch virus (TEV) includes an internal ribosome entry site (IRES). This allows ribosomes to dock, leading to the initiation of viral RNA translation.

The genus *Potyvirus* includes over two hundred members and is classified as one of the most extensive plant virus family – *Potyviridae* [56]. The genome of *Potyvirus* is comprised of approximately 10 kb positive-sense single stranded RNA molecule, covalently connected to a viral protein (VPg) at the 5' end via a tyrosine residue [57], and poly(A) tail at the 3' end [58-60]. The *potyviral* RNA contains a single open reading frame, translated into a large polyprotein, proteolytically cleaved into mature proteins by specific virus-encoded proteases [61]. This viral protein is known to serve as an analog of the 5'-m7G cap of the mRNAs, and has been shown to play an important role in mRNA translation since it interacts with the cap-binding proteins (e.g., eIF4E, eIFiso4E, eIF4F, eIFiso4F) [62,63]. VPg is vital for the infectivity of the virus [64], cell-to-cell movement [65-68], and has been linked to an array of other viral functions. Khan et al. [69] have revealed that potyviral VPg stimulates the *in vitro* translation of uncapped IRES-containing RNA, while inhibiting capped RNA translation in wheat germ extract. These effects have shown to be dependent on VPg-eIF4E(4F) or VPg-eIFiso4E(4F) interactions. These studies demonstrate that VPg competes for the cap-binding site in these translation initiation factors. Binding studies [63] show that VPg and cap bind competitively to eIFiso4E.

Interactions between pokeweed antiviral protein and *potyviral* protein

Recent studies examined the interactions between PAP (cap-binding protein) and VPg from TuMV [70], and revealed that VPg competes with TEV RNA for PAP binding [71]. These PAP-VPg interactions are enthalpically-driven and entropically favorable [70], exhibiting a similarity to those of eIFiso4E- and eIFiso4F-VPg binding [63]. Moreover, PAP demonstrated greater affinity for this viral protein, as compared to m7GTP-cap analog [35] and eIFiso4F [63]. PAP, having greater binding affinity for VPg than that for the cap structure, would certainly create an advantage for the cell if VPg were to target PAP toward viral RNA for depurination. Interestingly, we have determined that VPg displays strong inhibitory effect on PAP's activity, decreasing

the amounts of purines released from different RNAs (SRL oligo RNA, TEV RNA and luciferase mRNA) [70], implying that VPg may contribute to a viral strategy of overcoming one of the potential host cell defence mechanisms – the depurinating activity of PAP. This is further supported by Baldwin et al. [35], and solidifies the accepted function of PAP as a RIP.

Conclusion

Generally, viral RNA is translated less efficiently than capped host RNA, and has to compete for available cell resources to sustain translation. Formation of VPg-eIFiso4F complex would lead to a non-productive complex, reducing host cell protein synthesis. Conversely, VPg-eIF4F complex would also lead to the inhibition of capped mRNA translation, but in this case the complex would bind more tightly to IRES-containing mRNA leading to the preferential production of viral protein [63]. These complementary functions offer a significant competitive advantage for viral RNA translation. Plant-pathogen interactions continuously drive rapid evolutionary changes on both sides of the interactions. Plants produce toxic proteins that help them in battle viruses; meanwhile, viruses develop even more elaborate strategies to overcome these plant defence mechanisms. Here we see an example of how viral genome-linked protein may confer resistance to plant defence mechanisms. Further studies of VPg inhibitory effects on the activity of other RIPs may provide researchers with new avenues to design novel and natural protein inhibitors of RIP cytotoxicity [22,70].

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References

1. Thatcher LF, Anderson JB, Singh KB (2005) Plant defense responses: what we have learnt from Arabidopsis? *Funct Plant Biol* 32: 1-19.
2. Jones JD, Dangl JL (2006) The plant immune system. *Nature* 444: 323-329.
3. Anderson JB, Gleason CA, Foley RC, Thrall PH, Burdon JB, et al. (2010) Plants versus pathogens: an evolutionary arms race. *Funct Plant Biol* 37: 499-512.
4. Hardham AR, Jones DA, Takemoto D (2007) Cytoskeleton and cell wall function in penetration resistance. *Curr Opin Plant Biol* 10: 342-348.
5. Thordal-Christensen H (2003) Fresh insights into processes of nonhost resistance. *Curr Opin Plant Biol* 6: 351-357.
6. Morrissey JP, Osbourn AE (1999) Fungal resistance to plant antibiotics as a mechanism of pathogenesis. *Microbiol Mol Biol Rev* 63: 708-724.
7. Bednarek P, Osbourn A (2009) Plant-microbe interactions: chemical diversity in plant defence. *Science* 324: 746-748.
8. Stirpe F (2013) Ribosome-inactivating proteins: from toxins to useful proteins. *Toxicon* 67: 12-16.
9. Olsnes S (2004) The history of ricin, abrin and related toxins. *Toxicon* 44: 361-370.
10. Peumans WJ, Hao Q, Van Damme EJ (2001) Ribosome-inactivating proteins from plants: more than RNA N-glycosidases? *FASEB J* 15: 1493-1506.
11. Endo Y, Mitsui K, Motizuki M, Tsurugi K (1987) The mechanism of action of ricin and related toxic lectins on eukaryotic ribosomes. The site

- and the characteristics of the modification in 28S ribosomal RNA caused by the toxins. *J Biol Chem* 262: 5908-5912.
12. Mansouri S, Nourollahzadeh E, Hudak KA (2006) Pokeweed antiviral protein deurinates the sarcin/ricin loop of the rRNA prior to binding of aminoacyl-tRNA to the ribosomal A-site. *RNA* 12: 1683-1692.
 13. Irvin JD (1975) Purification and partial characterization of the antiviral protein from *Phytolacca americana* which inhibits eukaryotic protein synthesis. *Arch Biochem Biophys* 169: 522-528.
 14. Fordham-Skelton AP, Taylor PN, Hartley MR, Croy RR (1991) Characterisation of saporin genes: in vitro expression and ribosome inactivation. *Mol Gen Genet* 229: 460-466.
 15. Ready MP, Brown DT, Robertus JD (1986) Extracellular localization of pokeweed antiviral protein. *Proc Natl Acad Sci USA* 83: 5053-5056.
 16. Sandvig K, van Deurs B (1999) Endocytosis and intracellular transport of ricin: recent discoveries. *FEBS Lett* 452: 67-70.
 17. Roberts LM, Smith DC (2004) Ricin: the endoplasmic reticulum connection. *Toxicol* 44: 469-472.
 18. Bonness MS, Ready MP, Irvin JD, Mabry TJ (1994) Pokeweed antiviral protein inactivates pokeweed ribosomes; implications for the antiviral mechanism. *Plant J* 5: 173-183.
 19. Tumer NE, Hwang DJ, Bonness M (1997) C-terminal deletion mutant of pokeweed antiviral protein inhibits viral infection but does not deurate host ribosomes. *Proc Natl Acad Sci USA* 94: 3866-3871.
 20. Mundy J, Leah R, Boston R, Endo Y, Stirpe F (1994) Genes encoding ribosome-inactivating proteins. *Plant Mol Biol Rep* 12: S60-S62.
 21. Barbieri L, Battelli MG, Stirpe F (1993) Ribosome-inactivating proteins from plants. *Biochim Biophys Acta* 1154: 237-282.
 22. Domashevskiy AV, Goss DJ (2015) Pokeweed antiviral protein, a ribosome inactivating protein: activity, inhibition and prospects. *Toxins (Basel)* 7: 274-298.
 23. Olsnes S, Pihl A (1973) Isolation and properties of abrin: a toxic protein inhibiting protein synthesis. Evidence for different biological functions of its two constituent-peptide chains. *Eur J Biochem* 35: 179-185.
 24. Olsnes S, Pihl A (1981) Chimeric toxins. *Pharmacol Ther* 15: 355-381.
 25. Hazes B, Read RJ (1997) Accumulating evidence suggests that several AB-toxins subvert the endoplasmic reticulum-associated protein degradation pathway to enter target cells. *Biochemistry* 36: 11051-11054.
 26. Lord JM, Roberts LM (1998) Toxin entry: retrograde transport through the secretory pathway. *J Cell Biol* 140: 733-736.
 27. Bass HW, Webster C, O'Brien GR, Roberts JK, Boston RS (1992) A maize ribosome-inactivating protein is controlled by the transcriptional activator Opaque-2. *Plant Cell* 4: 225-234.
 28. Chaudhry B, Muller-Uri F, Cameron-Mills V, Gough S, Simpson D, et al. (1994) The barley 60 kDa jasmonate-induced protein (JIP60) is a novel ribosome-inactivating protein. *Plant J* 6: 815-824.
 29. Reinbothe S, Reinbothe C, Lehmann J, Becker W, Apel K, et al. (1994) JIP60, a methyl jasmonate-induced ribosome-inactivating protein involved in plant stress reactions. *Proc Natl Acad Sci USA* 91: 7012-7016.
 30. Walsh TA, Morgan AE, Hey TD (1991) Characterization and molecular cloning of a proenzyme form of a ribosome-inactivating protein from maize. Novel mechanism of proenzyme activation by proteolytic removal of a 2.8-kilodalton internal peptide segment. *J Biol Chem* 266: 23422-23427.
 31. Lin Q, Chen ZC, Antoniw JF, White RF (1991) Isolation and characterization of a cDNA clone encoding the anti-viral protein from *Phytolacca americana*. *Plant Mol Biol* 17: 609-614.
 32. Irvin JD, Uckun FM (1992) Pokeweed antiviral protein: ribosome inactivation and therapeutic applications. *Pharmacol Ther* 55: 279-302.
 33. Poyet JL, Radom J, Hoeveler A (1994) Isolation and characterization of a cDNA clone encoding the pokeweed antiviral protein II from *Phytolacca americana* and its expression in *E. coli*. *FEBS Lett* 347: 268-272.
 34. Rajamohan F, Engstrom CR, Denton TJ, Engen LA, Kourinov I, et al. (1999) High-level expression and purification of biologically active recombinant pokeweed antiviral protein. *Protein Expr Purif* 16: 359-368.
 35. Baldwin AE, Khan MA, Tumer NE, Goss DJ, Friedland DE (2009) Characterization of pokeweed antiviral protein binding to mRNA cap analogs: competition with nucleotides and enhancement by translation initiation factor iso4G. *Biochim Biophys Acta* 1789: 109-116.
 36. Poyet JL, Hoeveler A (1997) cDNA cloning and expression of pokeweed antiviral protein from seeds in *Escherichia coli* and its inhibition of protein synthesis in vitro. *FEBS Lett* 406: 97-100.
 37. Barbieri L, Aron GM, Irvin JD, Stirpe F (1982) Purification and partial characterization of another form of the antiviral protein from the seeds of *Phytolacca americana* L. (pokeweed). *Biochem J* 203: 55-59.
 38. Honjo E, Dong D, Motoshima H, Watanabe K (2002) Genomic clones encoding two isoforms of pokeweed antiviral protein in seeds (PAP-S1 and S2) and the N-glycosidase activities of their recombinant proteins on ribosomes and DNA in comparison with other isoforms. *J Biochem* 131: 225-231.
 39. Hartley MR, Lord JM (2004) Genetics of ribosome-inactivating proteins. *Mini Rev Med Chem* 4: 487-492.
 40. Girbes T, Ferreras JM, Arias FJ, Stirpe F (2004) Description, distribution, activity and phylogenetic relationship of ribosome-inactivating proteins in plants, fungi and bacteria. *Mini Rev Med Chem* 4: 461-476.
 41. Battelli MG, Citores L, Buonamici L, Ferreras JM, de Benito FM, et al. (1997) Toxicity and cytotoxicity of nigrin b, a two-chain ribosome-inactivating protein from *Sambucus nigra*: comparison with ricin. *Arch Toxicol* 71: 360-364.
 42. Dallal JA, Irvin JD (1978) Enzymatic inactivation of eukaryotic ribosomes by the pokeweed antiviral protein. *FEBS Letters* 89: 257-259.
 43. Aitbakieva VR, Domashevskiy AV (2016) Insights into the molecular antiviral mechanism of pokeweed protein from *phytolacca americana*. *Biochem Pharmacol (Los Angel)* 5: 210.
 44. Rajamohan F, Venkatachalam TK, Irvin JD, Uckun FM (1999) Pokeweed antiviral protein isoforms PAP-I, PAP-II, and PAP-III deurate RNA of human immunodeficiency virus (HIV)-1. *Biochem Biophys Res Commun* 260: 453-458.
 45. Mansouri S, Choudhary G, Sarzala PM, Ratner L, Hudak KA (2009) Suppression of human T-cell leukemia virus I gene expression by pokeweed antiviral protein. *J Biol Chem* 284: 31453-31462.
 46. Aron GM, Irvin JD (1980) Inhibition of herpes simplex virus multiplication by the pokeweed antiviral protein. *Antimicrob Agents Chemother* 17: 1032-1033.
 47. Picard D, Kao CC, Hudak KA (2005) Pokeweed antiviral protein inhibits brome mosaic virus replication in plant cells. *J Biol Chem* 280: 20069-20075.
 48. Tomlinson JA, Walker VM, Flewett TH, Barclay GR (1974) The inhibition of infection by cucumber mosaic virus and influenza virus by extracts from *Phytolacca americana*. *J Gen Virol* 22: 225-232.
 49. He YW, Guo CX, Pan YF, Peng C, Weng ZH (2008) Inhibition of hepatitis B virus replication by pokeweed antiviral protein in vitro. *World J Gastroenterol* 14: 1592-1597.
 50. Ussery MA, Irvin JD, Hardesty B (1977) Inhibition of poliovirus replication by a plant antiviral peptide. *Ann NY Acad Sci* 284: 431-440.
 51. Dreher TW, Miller WA (2006) Translational control in positive strand RNA plant viruses. *Virology* 344: 185-197.
 52. Dreher TW (2009) Role of tRNA-like structures in controlling plant virus replication. *Virus Res* 139: 217-229.
 53. Gallie DR, Kobayashi M (1994) The role of the 3'-untranslated region of non-polyadenylated plant viral mRNAs in regulating translational efficiency. *Gene* 142: 159-165.
 54. Zeenko V, Gallie DR (2005) Cap-independent translation of tobacco etch virus is conferred by an RNA pseudoknot in the 5'-leader. *J Biol Chem* 280: 26813-26824.
 55. Gallie DR, Tanguay RL, Leathers V (1995) The tobacco etch viral 5' leader and poly(A) tail are functionally synergistic regulators of translation. *Gene* 165: 233-238.

56. van Regenmortel MH, Fauquet CM, Bishop DH, Carstens EB, Esters MK, et al. (2000) *Virus Taxonomy: Seventh report of the International Committee on Taxonomy of Viruses*. Academic Press, San Diego, USA.
57. Murphy JF, Rychlik W, Rhoads RE, Hunt AG, Shaw JG (1991) A tyrosine residue in the small nuclear inclusion protein of tobacco vein mottling virus links the VPg to the viral RNA. *J Virol* 65: 511-513.
58. Goodfellow I, Chaudhry Y, Gioldasi I, Gerondopoulos A, Natoni A, et al. (2005) Calicivirus translation initiation requires an interaction between VPg and eIF4E. *EMBO Rep* 6: 968-972.
59. Leonard S, Plante D, Wittmann S, Daigneault N, Fortin MG, et al. (2000) Complex formation between potyvirus VPg and translation eukaryotic initiation factor 4E correlates with virus infectivity. *J Virol* 74: 7730-7737.
60. Daughenbaugh KF, Fraser CS, Hershey JW, Hardy ME (2003) The genome-linked protein VPg of the Norwalk virus binds eIF3, suggesting its role in translation initiation complex recruitment. *EMBO J* 22: 2852-2859.
61. Urcuqui-Inchima S, Haenni AL, Bernardi F (2001) Potyvirus proteins: a wealth of functions. *Virus Res* 74: 157-175.
62. Wittmann S, Chatel H, Fortin MG, Laliberte JF (1997) Interaction of the viral protein genome linked of turnip mosaic potyvirus with the translational eukaryotic initiation factor (iso)4E of *Arabidopsis thaliana* using the yeast two-hybrid system. *Virology* 234: 84-92.
63. Khan MA, Miyoshi H, Ray S, Natsuaki T, Suehiro N, et al. (2006) Interaction of genome-linked protein (VPg) of turnip mosaic virus with wheat germ translation initiation factors eIFiso4E and eIFiso4F. *J Biol Chem* 281: 28002-28010.
64. Murphy JF, Klein PG, Hunt AG, Shaw JG (1996) Replacement of the tyrosine residue that links a potyviral VPg to the viral RNA is lethal. *Virology* 220: 535-538.
65. Rajamaki ML, Valkonen JP (2002) Viral genome-linked protein (VPg) controls accumulation and phloem-loading of a potyvirus in inoculated potato leaves. *Mol Plant Microbe Interact* 15: 138-149.
66. Rajamaki ML, Valkonen JP (1999) The 6K2 protein and the VPg of potato virus A are determinants of systemic infection in *Nicotiana glauca*. *Mol Plant Microbe Interact* 12: 1074-1081.
67. Schaad MC, Carrington JC (1996) Suppression of long-distance movement of tobacco etch virus in a nonsusceptible host. *J Virol* 70: 2556-2561.
68. Schaad MC, Lellis AD, Carrington JC (1997) VPg of tobacco etch potyvirus is a host genotype-specific determinant for long-distance movement. *J Virol* 71: 8624-8631.
69. Khan MA, Miyoshi H, Gallie DR, Goss DJ (2008) Potyvirus genome-linked protein, VPg, directly affects wheat germ in vitro translation: interactions with translation initiation factors eIF4F and eIFiso4F. *J Biol Chem* 283: 1340-1349.
70. Domashevskiy AV, Miyoshi H, Goss DJ (2012) Inhibition of pokeweed antiviral protein (PAP) by turnip mosaic virus genome-linked protein (VPg). *J Biol Chem* 287: 29729-29738.
71. Domashevskiy AV, Cheng SY (2015) Thermodynamic Analysis of Binding and Enzymatic Properties of Pokeweed Antiviral Protein (PAP) toward Tobacco Etch Virus (TEV) RNA. *J Nat Sci* 1: e82.