

Review

Sonic Hedgehog Is a Member of the Hh/DD-Peptidase Family That Spans the Eukaryotic and Bacterial Domains of Life

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Abstract: Sonic Hedgehog (Shh) coordinates Zn^{2+} in a manner that resembles that of peptidases. The ability of Shh to undergo autoproteolytic processing is impaired in mutants that affect the Zn^{2+} coordination, while mutating residues essential for catalytic activity results in more stable forms of Shh. The residues involved in Zn^{2+} coordination in Shh are found to be mutated in some individuals with the congenital birth defect holoprosencephaly, demonstrating their importance in development. Highly conserved Shh domains are found in parts of some bacterial proteins that are members of the larger family of DD-peptidases, supporting the notion that Shh acts as a peptidase. Whereas this Hh/DD-peptidase motif is present in Hedgehog (Hh) proteins of nearly all animals, it is not present in *Drosophila* Hh, indicating that Hh signaling in fruit flies is derived, and perhaps not a good model for vertebrate Shh signaling. A sequence analysis of Hh proteins and their possible evolutionary precursors suggests that the evolution of modern Hh might have involved horizontal transfer of a bacterial gene coding of a Hh/DD-peptidase into a *Cnidarian* ancestor, recombining to give rise to modern Hh.

Keywords: Sonic Hedgehog; bacterial Hedgehog; *Drosophila* Hedgehog; Zn^{2+} peptidase; DD-peptidase; Hedgehog evolution

1. The Sonic Hedgehog Pro-Protein Gives Rise to the Mature Ligand after an Autoproteolytic Cleavage Event

The *Hedgehog* (*Hh*) gene was first identified in the now famous developmental *Drosophila melanogaster* screen performed by Christiane Nüsslein-Volhard and Eric Wieschaus in the late 1970s. The screen used a technique known as “saturation mutagenesis” to isolate the genes involved in the formation of the *Drosophila* body plan [1]. *Hh* mutant larvae have a solid lawn of denticles on the cuticle rather than stripes of denticles on the anterior half of each segment, hence the name “hedgehog”. Like other segment polarity genes found in this screen, *Hh* genes are also widely conserved among animals, and mammals have three Hh paralogs (Sonic, Indian, and Desert Hedgehog) that, like in *Drosophila*, play central roles in development [2].

Sonic Hedgehog (Shh) coordinates a Zn^{2+} metal ion with H141, D148, and H183 (mouse numbering, Figure 1) residues that are typical for Zn^{2+} peptidases [3], such as the bacterial peptidase, thermolysin [4]. Like many peptidases, the Shh undergoes an intramolecular auto-processing reaction resulting in cleavage between G198 and C199. As a consequence of this cleavage event, the N-terminal product of this cleavage (ShhN), is modified with cholesterol [5,6]. Subsequently Shh is modified by N-terminal acylation [7–9], rendering ShhN_{chol} obligatory membrane bound. Secretion of this form of Shh requires Disp1 and Scube2 [10] and ADAM-type metalloproteases, yielding a form that is stripped of its lipid modifications and active in signaling [11,12] (Figure 1).

Whereas ShhN harbors the Zn^{2+} peptidase motif, the carboxyterminal domain has similarities to self-splicing bacterial inteins [13]. These inteins typically cleave before a cysteine residue through the resolution of a thio-ester intermediate [6]. The G198/C199 site of cleavage is consistent with this idea. Single amino acid changes in C-terminal domains can prevent auto-processing, resulting in the perdurance of the Shh pro-protein [14]. Similarly, mutations of the residues that directly mediate Zn^{2+} coordination prevent the autoproteolytic processing of the Shh [15] and thermolysin pro-proteins [16]. There thus appear to be structural requirements in both the ShhC and ShhN domains for auto-processing to proceed, perhaps indicating that overlapping/complementary endopeptidase activities associated with the ShhN and -C domains are involved in autocatalytic processing. The inherent endopeptidase activity of Shh is coupled to the addition of a cholesterol moiety to ShhN ($ShhN_{Chol}$), which affects the distribution of the ligand [17]. Interestingly, many of the Zn^{2+} peptidase catalytic residues are not required for signaling by ShhN [18], and consequently, the Zn^{2+} coordination domain of Shh has been referred to as the “pseudo active” site [19,20]. Nevertheless, the importance of the Zn^{2+} coordination domain has become apparent as mutations of this domain have been associated with congenital malformations, demonstrating their role in development.

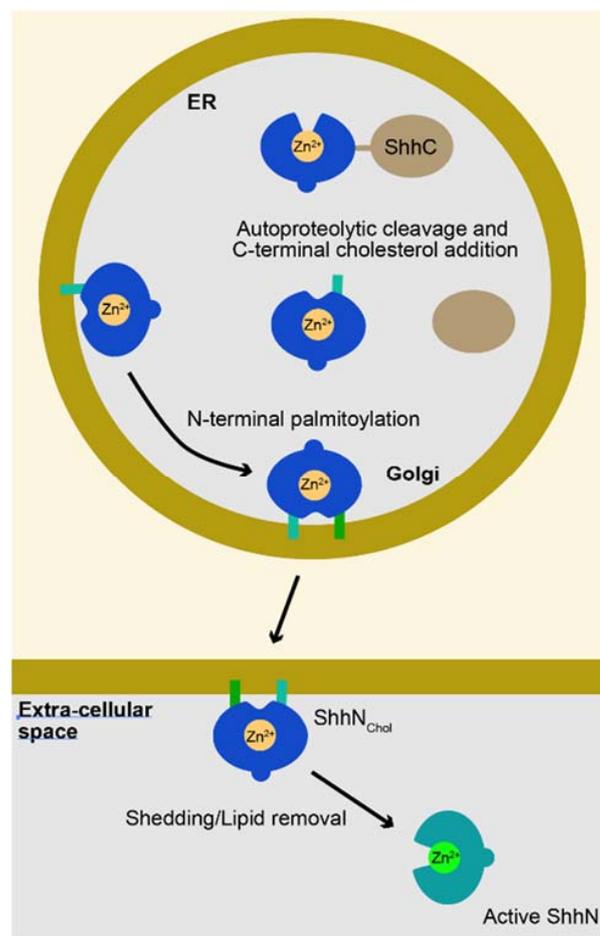


Figure 1. Diagram of the Sonic Hedgehog (Shh) processing/maturation steps. Shh is translated into a pro-protein, consisting of a ShhN and ShhC domain, that undergoes an autoproteolytic processing event prior to entry into the Golgi. This results in the attachment of a cholesterol moiety to the ShhN domain, likely shielding the Zn^{2+} coordination domain. In the Golgi, $ShhN_{chol}$ is further lipidated by a palmitoyl chain (green bars), further forcing its membrane association. Release and shedding are regulated processes involving Disp1, Scube2 and ADAM metalloproteases, resulting in the release of Shh devoid of its lipid moieties, with its Zn^{2+} coordination domain exposed.

3. Shh Has All the Hallmarks of a DD-Peptidase

The notion that Shhs are pseudo-proteases is primarily based on studies claiming that the Zn^{2+} coordination site is required to maintain the correct and stable Shh structure and for Shh to bind to Ptch1 [24], but it does not mediate protease activity [18]. This rejection of the Shh protease function was based on one experiment with a negative outcome, which used simple biochemical assays using artificial peptide substrates, common peptidase inhibitors, and *E. coli* expressed non-lipidated ShhN mutants that were not derived from the Shh pro-protein. Under such experimental conditions, even testing established proteases would possibly fail to reveal their proteolytic activities. A possibly more useful approach would be to more precisely determine the effects of Robotnikinin, a small molecule that binds to the Shh Zn^{2+} coordinating domain [25] at high nanomolar concentrations [26], in cells that lack Ptch function.

In Zn^{2+} peptidases, the E177 equivalent abstracts a proton from the catalytic water at the Zn^{2+} coordination domain, which is followed by a nucleophilic attack of the OH^- on the peptide backbone. Shh-E177A is, therefore, predicted to be impaired for the intrinsic Zn^{2+} peptidase activity. Analysis of this mutant has revealed two interesting properties. First, Shh-E177A is unable to mediate signaling from the notochord to the overlying neural tube (*in trans*), but is more capable than Shh of inducing the Hh response when expressed in the developing neural tube (likely *in cis*) [27]. Second, purified ShhN-E177A is more stable in solution than ShhN, indicating a cannibalistic peptidase activity that is intrinsic to ShhN. This activity is inhibited by the binding of one or two Ca^{2+} ions [4] to ShhN (Figure 2A), using a binding motif that is conserved among Hh proteins and present in thermolysin. It appears that interfering with the putative Zn^{2+} peptidase activity either via the Zn^{2+} coordination domain or E177 has negative consequences for Shh signaling during development, indicating a role for this peptidase activity-associated residue for normal Shh function.

The conservation of the Zn^{2+} coordinating, Ca^{2+} coordinating and other catalytic residues throughout evolution supports the possibility that Hhs are not pseudo-proteases but, the properly matured form with the endogenous substrate, may indeed act as peptidases. Furthermore, a structural analysis of interactions between Shh and its Hh interacting protein (Hhip) showed that they resemble molecular interactions between matrix metalloproteases (MMPs) and the tissue inhibitor of metalloproteinase (TIMP). In both cases, a loop present in Hhip and TIMP interacts closely with the ShhN-coordinated Zn^{2+} , thus blocking catalytic activity. This striking similarity between unrelated protease/inhibitor pairs further supports the notion that ShhN is a Zn^{2+} peptidase; not only is an active site present, but interactions of this site with Hhip and possibly, Ptch1 also resemble established metalloprotease/inhibitor interactions [19].

As is typical for a protease active site, the Zn^{2+} in ShhN sits at the bottom of a cleft and is exposed to solvent and not hidden inside of the molecule. This configuration is conserved in the mature form of the well-characterized protease, thermolysin [3]. ShhN homologs in bacteria are characterized by a conserved Zn^{2+} coordination motif which defines a family of prokaryotic proteins that are characterized by the DD-peptidase fold [28]. The signature peptidase fold is a central, five-stranded, antiparallel β -sheet, separating the Zn^{2+} coordination domain from several α -helices, as found in ShhN (Figure 2A). Members of this family include murein endopeptidase (penicillin resistant enzymes) and peptidase M15 (bacterial D-alanyl-D-alanine carboxypeptidases (DD-peptidase), the target for penicillin) [28]. Both these peptidases play critical roles in bacterial cell wall modification. Shh and peptidase M15 share the two histidine residues and an aspartic acid residue that mediate Zn^{2+} coordination (H141 D148, H183 for Shh). The overall Zn^{2+} coordination motif is also found in lysostaphin, another peptidase that cleaves peptide bonds in bacterial peptidoglycan, and is referred to as the "LAS" (Lysostaphin, D-alanyl-D-alanine carboxypeptidase, Shh) arrangement [29]. DD-peptidases characteristically contain an H-X(6)-D and an H-X-H motif that coordinate Zn^{2+} into an accessible catalytic cleft. Based on all of these criteria, Shh is a member of this class of peptidases [28], further supporting the notion that Shh can function as a protease, perhaps even targeting a glycoprotein. Characterized bacterial DD-peptidases use a catalytic mechanism in which the acyl-linked peptide-enzyme intermediate is resolved by a

nucleophilic attack of the adjacent peptidoglycan chain, thus cross-linking the peptidoglycan chains in the bacterial cell wall, and it remains to be determined if Shh has a similar activity.

4. Several Bacterial Species Have Highly Conserved HhN Domains

Remarkably, several species of bacteria carry highly conserved Hedgehog proteins with unknown function (Figures 3 and 4 and Supplementary file). An approximately 145 amino acid domain comprising the bulk of ShhN (Figure 3, green box) and containing the typical DD-peptidase motif has over 50% identity to some bacterial proteins (Figure 4B), and this class of protein domains will be referred to as bacHhs. All the residues involved in Zn²⁺ and Ca²⁺ coordination are identical, as is E177, a residue required for non-autonomous Shh signaling. In bacteria, the Hh/DD-peptidases domain is the C-terminal part of larger proteins. Homologs of the N-terminal domains of the bacterial Hh proteins can be found to be associated with different subtypes of Zn²⁺ peptidases throughout bacteria (Figure 4A). In a few bacterial species, including some *Rhizobium* and *Bradyrhizobium* species, the N-terminal part preceding the Hh/DD-peptidase domain is predicted to contain three transmembrane regions, placing the Hh domain in the periplasmic space (Figure 4A). In this configuration, the third transmembrane domain of *Rhizobium* bacHh lines up perfectly with the signal sequence of Shh. No clear homologs of the Hh receptors, Patched and Smoothed, are present in any of these bacteria, or their *Rhizobium Legume* hosts, further supporting the idea that bacHhs serve as peptidases, rather than as ligands. The similarity of ShhN to its bacterial counterparts is as high as to other distant metazoan Hhs, and higher than its similarity to the *Cnidarian* hedgling N-domain and *Drosophila* HhN (Figure 4B). Given the high degree of similarity between Shh and its bacterial counterparts, it is likely that they share a specific function. The relatively small number of sequenced bacteria with a highly conserved HhN domain (I found about a dozen) do not share any obvious characteristics or ecological niches, and the precise function of this bacHh peptidase activity remains unknown.

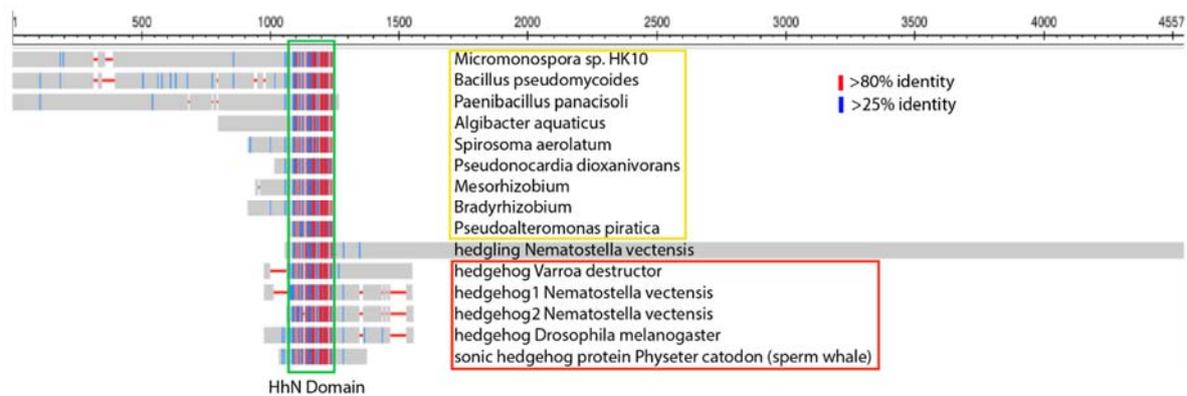


Figure 3. HhN domains are present in bacteria. Lineup of several hypothetical proteins in bacteria, Hedgling and metazoan Hhs. The conserved domain (HhN, green box, about 175 residues) is flanked by other sequences in the various species. In bacteria (yellow box) the HhN domain is the C-terminal end of the hypothetical proteins. The HhN domain is the N-terminal part of Hedgling and Hhs (red box). The blue and red lines indicate medium and high levels of conservation. Accession numbers of the aligned proteins are in the Supplementary file.

5. What Are the Possible Substrates for the Shh Peptidase Activity?

The general properties of bacterial DD-peptidases and lysostaphins as modifiers of the bacterial cell wall are likely shared with the bacHhs. The peptidoglycans that are a major component of the bacterial periplasmic space have some similarities to the proteoglycans that are common in the insect and vertebrate extracellular matrix. Both bacterial cell wall peptidoglycans and animal matrix proteoglycans are large molecules in which polypeptides are covalently attached to chains of glycans. In particular, the matrix heparin sulfate proteoglycans (HSPGs) bind Shh and can both negatively and positively affect the Shh response [30–32]. Furthermore, mutations in *ext* genes that code for glycosyltransferases that catalyze glycosaminoglycan in addition to the core protein disrupt Hh signaling in vertebrates [33] and insects [34]. It is thus possible that functional conservation between bacHhs and Shh is reflected in the ability of Shh to cleave or modify proteoglycans, thus affecting the Shh response or distribution, independent of binding to the canonical receptors.

Although any Shh antagonist could be a possible target for Shh peptidase activity, both Hhip and Ptch1 are unlikely substrates, as they have the characteristics of metalloprotease inhibitors [19].

6. *Drosophila* Hh Is Not a Member of the Hh/DD-Peptidase Family

Drosophila Hh (dmHh) has been the guide molecule for all Hh signaling since the discovery that it is necessary for embryogenesis [1]. However, dmHh is unusual in that it does not have the core sequences H-X(6)-D, H-X-H that define the Hh/DD-peptidase motif, but instead, dmHh has H-X(6)-T, H-X-Y. Furthermore, the catalytically important E177 (mouse numbering) is mutated in dmHh into a valine residue. The absence of the Hh/DD-peptidase motif is unique to all sequenced *Drosophilids*; searching with the *Drosophila* sequence that encompasses the DD-peptidase motif (ESLHYEGRAVTIATSDRDQSKYGMLARLAVEAGFDWVSYVSRRHLYCSVKS) places *Drosophilids* as an outgroup to all other arthropods and deuterostomes. *Drosophilids* are the outlier because Hh proteins in all other protostomes and deuterostomes retain the conserved Hh/DD-peptidase Zn²⁺ coordination motif. Searching with a hypothetical *dmHh* peptide that conforms to the Hh/DD-peptidase motif and E177 does no longer uniquely group with the *Drosophilids*, and has similar homology to several vertebrate and insect Hhs. Given the high degree of HhN conservation between bacteria and eukaryotes (Figure 3), the most plausible explanation for this is that *Drosophilids* have lost some of the activities associated with the ancestral Zn²⁺ coordination domain. The loss of Zn²⁺ coordinating residues in conjunction with the E177 homolog is no surprise in light of the likely loss of peptidase activity in *Drosophila* Hh. The observation that vertebrate Shh is active in *Drosophila* embryos [35], but *Drosophila* Hh is not active in vertebrates, further supports the notion that some aspects of Hh signaling present in most animals are lost in fruit flies, but that both proteins can bind to Ptch. These observations question to what extent the lessons learned in *Drosophila* embryos regarding Hh processing and signaling can be directly applied to vertebrates, or even other arthropods, as all these animals maintain an intact Hh/DD-peptidase domain. The study of Hh signaling in another insect, such as *Tribolium* [36], might help to resolve how *Drosophila* Hh signaling is impacted by the loss of the DD-peptidase motif in the ligand.

7. The Presence of bacHhs Suggests an Alternative Hypothesis Regarding the Evolution of Modern Hh

Hh genes are present in *Cnidarians* (corals and jellyfish), but not in sponges and protozoa [37]. However, another class of proteins that contain an N-terminal HhN-like domain is the Hedgling proteins that can be found in *Cnidarians*, sponges and *Choanoflagellates* [38], which are protozoans. In these Hedgling proteins, the HhN domain is followed by a large C-terminal domain that is related to cell adhesion molecules. A plausible evolutionary path is that the HhN domain of Hedgling was recombined to a Hog domain that is present in most genomes (Figure 5 green arrows). However, the HhN domain of Hedgling does not contain a complete Hh/DD-peptidase motif, whereas, it is likely that its putative ancestral form in the last universal common ancestor (LUCA) had an intact

Hh/DD-peptidase domain. Although this evolutionary path from a LUCA DD-peptidase via Hedgling to Hh could have conceivably occurred without horizontal gene transfer (Figure 5, green arrows), it would have required several recombination events. The first event would have entailed the recombination of the bacterial-like Hh domain from a DD-peptidase to form the Hedgling protein, and the second event would have involved recombination of the HhN domain of Hedgling into modern Hh. Following this potential evolutionary path, the Hh/DD-peptidase motif would have been lost in Hedgling and re-established in Hh.

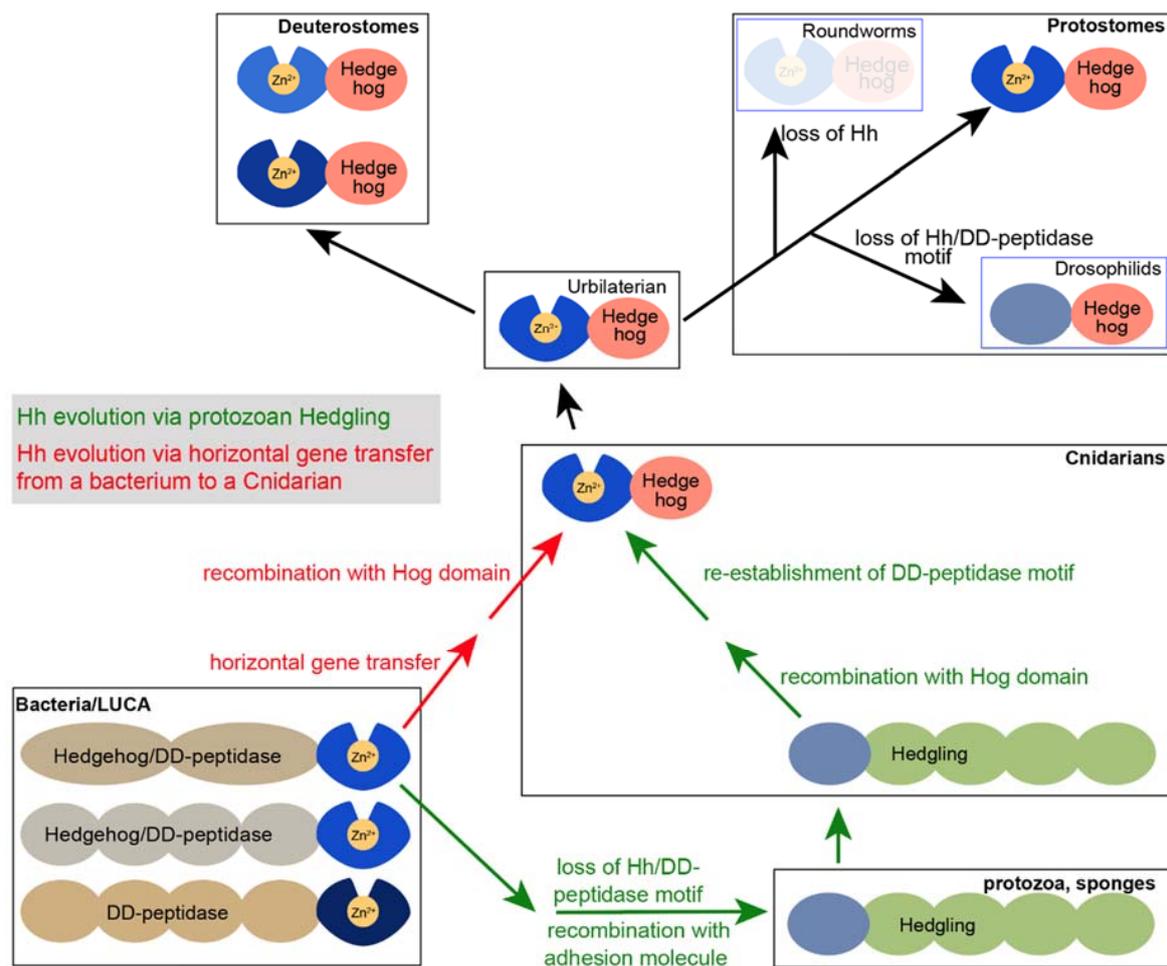


Figure 5. Models for the evolution of modern Hh proteins. The presence of both Hhs and Hedglings in Cnidarians support the model that the HhN of Hh domain arose via a recombination of the Hedgling N-domain. As Hedgling is present in at least some protozoa, it is plausible that it was derived from a DD-peptidase in the last universal common ancestor (LUCA). Alternatively, a Hh/DD-peptidase could have entered a Cnidarian ancestor from a bacterium via horizontal gene transfer, never losing the Zn²⁺ coordination in the process. Modern Hh was present in the Urbilaterian (the last common ancestor of protostomes and deuterostomes) and was retained in most of its offspring. The loss of the Hh/DD-peptidase motif in *Drosophilids* is derived, as is the loss of all Hh in some bilaterian protostomes (such as roundworms).

The presence of highly conserved HhN protein domains in bacteria suggests an alternate hypothesis, in which horizontal *bachHh/DD-peptidase* gene transfer from a bacterium to a *Cnidarian* ancestor was followed by recombination of the HhN domain with a *Cnidarian Hog* domain, resulting in a modern *Hh* gene (Figure 5, red arrows). This possible evolutionary path would have required only one recombination event and would not have involved the subsequent loss and re-establishment

of the Hh/DD-peptidase domain, as is indicated for the evolutionary path via Hedgling. As the more parsimonious explanation it is perhaps a more plausible path for the evolution of modern Hh. The higher conservation between ShhN and bacterial Hh/DD-peptidases than between ShhN and the N-domain of Hedgling lends further support to the horizontal gene transfer model.

8. Conclusions

Although the Zn²⁺ coordination domain of Shh is often referred to as its “pseudo catalytic” domain [19,39,40], the remarkable similarity of most Hhs to bacterial Hh/DD-peptidases further supports the notion that Shh functions as a peptidase during development. Some mutations found in holoprosencephaly patients break the Hh/DD-peptidase motif, and negatively affect Hh signaling, possibly by preventing autoproteolytic cleavage, indicating that the intrinsic Zn²⁺ peptidase activity of Shh is critical to its function. The lack of the Hh/DD-peptidase domain in *Drosophila* Hh demonstrates that it is evolutionary derived, and perhaps not the best model for Hh signaling in animals with the ancestral Hh/DD-peptidase motif, like humans and mice. Finally, the presence of HhN protein domains in some bacteria supports an alternate pathway for the evolution of Hh, via horizontal gene transfer from bacteria into an Urbilaterian ancestor, resulting in the modern Hh which has retained ancestral peptidase activity.

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