The cytochrome P450 CYP72A552 is key to production of hederagenin-based saponins that mediate plant defense against herbivores

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The cytochrome P450 CYP72A552 plays a key role in triterpenoid saponin mediated plant defense against herbivores

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Summary

Plants continuously evolve new defense compounds. One class of such compounds are triterpenoid saponins. A few species in the Barbarea genus produce saponins as the only ones in the large crucifer family. However, the molecular mechanism behind saponin biosynthesis and their role in plant defense remains unclear.

We used a combination of pathway reconstitution in planta, enzymatic production of saponins in vitro, insect feeding assays, and bioinformatics to identify a missing gene involved in saponin biosynthesis and saponin-based herbivore defense.

A tandem repeat of eight CYP72A cytochromes P450 co-localize with a QTL for saponin accumulation and flea beetle resistance in B. vulgaris. We found that CYP72A552 oxidizes oleanolic acid at position C-23 to hederagenin. In vitro produced hederagenin mono-glucosides reduced larval feeding by up to 90 % and caused 75 % larval mortality of the major crucifer pest diamondback moth and the tobacco hornworm. Sequence analysis indicate that CYP72A552 evolved through gene duplication and has been under strong selection pressure.

In conclusion, CYP72A552 has evolved to play an essential role in plant defense against herbivores. Our study highlights evolution of chemical novelties by gene duplication and selection for enzyme innovations, and the importance of chemical modification in plant defense evolution.

Key words: cytochrome P450, molecular evolution, triterpenoid saponin biosynthesis, plant-insect interaction, pathway elucidation
Introduction

Plants continuously evolve new defense compounds to survive in the arms race against herbivores. Saponins are one such class of specialized compounds. They consist of a hydrophobic triterpenoid backbone with one or more hydrophilic saccharide groups attached. Some saponins are toxic or deterrent to insects, molluscs, fungi, and other microorganisms, and have probably evolved for defense against these, although their mode of action and evolution is not fully understood (De Geyter et al., 2007). Research on different Lepidoptera (moths and butterflies) cell lines indicates that saponins can affect midgut cell membranes (De Geyter et al., 2012), which may explain their toxicity. In addition to cell membrane disruption, saponins can also act as deterrents to insect feeding due to their bitter taste (De Geyter et al., 2007; Augustin et al., 2012).

The ability to produce saponins has evolved convergently in several different plant families, testifying their biological significance. Within the large crucifer family (Brassicaceae), only a few species in the genus Barbarea are known to produce saponins (Badenes-Perez et al., 2013). One of the species, B. vulgaris, has diverged into two different “plant types” that differ in saponin profile and herbivore resistance, as well as in other defense-related traits (Kuzina et al., 2011; Hauser et al., 2012; Toneatto et al., 2012). One type, the G-type (Glabrous), is completely resistant to some specialist insect herbivores, including the devastating agricultural pest diamondback moth (Plutella xylostella) and the flea beetle (Phyllotreta nemorum). The other type, the P-type (Pubescent), is susceptible to these insects (Agerbirk et al., 2003; Kuzina et al., 2011). Due to the interesting defense properties of Barbarea, including an unusual glucosinolate profile, it has become a model for evolution and ecology of plant defense compounds (Augustin et al., 2011; Byrne et al., 2017).

Insect resistance in B. vulgaris correlates in dose-dependent manner with four triterpenoid saponins: the cellobiosides of hederagenin, oleanolic acid, gypsogenin, and 4-epi-hederagenin (Shinoda et al., 2002; Agerbirk et al., 2003; Kuzina et al., 2009) (Fig. 1a). These four saponins are constitutively present and can be induced to elevated levels upon insect and pathogen attack (van Mölken et al., 2014). Among these saponins, hederagenin cellobioside is especially toxic or deterrent, as indicated by feeding assays with purified compounds painted on radish leaf discs (Renwick, 2002; Badenes-Perez et al., 2013). In comparison, oleanolic acid cellobioside, which differs
from hederagenin celllobioside only by the lack of a C-23 alcohol group, has much less
effect (Nielsen et al., 2010).

Knowledge of genes and enzymes involved in the biosynthesis of saponins is
incomplete. According to a proposed model, the omnipresent precursor 2,3-
oxidosqualene is cyclized to a limited number of core structures, which are
subsequently decorated with functional groups, and finally, sugars are added (Seki et
al., 2015). Oxidosqualene cyclases (OSCs) catalyze the first committed step in the
pathway forming the core structures, to which functional oxygenated groups are added
by cytochromes P450 (P450s), and sugars by UDP- glycosyltransferases (UGTs) (Seki
et al., 2015).

Several studies have made significant progress in uncovering genes and enzymes
involved in saponin biosynthesis and the associated flea beetle resistance in B. vulgaris.
Two OSCs, LUP5 and LUP2, have been identified and characterized from G- and P-
type plants. LUP5 is preferentially expressed in G-type (flea beetle resistant) plants and
produces mainly β-amyrin, the backbone of the resistance-conferring oleane-type
saponins. LUP2 is preferentially expressed in P-type (insect herbivore susceptible)
plants and produces mainly lupeol, the backbone of lupeol-type saponins (Khakimov et
al., 2015), for which we do not know any biological function in B. vulgaris. Other OSCs
with similar function have been reported from licorice, ginseng, lotus, Arabidopsis
thaliana, etc. (Kushiro et al., 1998; Hayashi et al., 2001; Husselstein–Muller et al.,
2001; Sawai et al., 2006). The P450s CYP716A80 and CYP716A81 from the G-type
and P-type, respectively, oxidizes β-amyrin at the C-28 position to oleanolic acid, the
precursor of hederagenin (Khakimov et al., 2015). Several UDP-glycosyltransferases
from the UGT73C subfamily in B vulgaris have been isolated (Augustin et al., 2012;
Erthmann et al., 2018). Among them, UGT73C11 and its ortholog UCT73C10 have
evolved to specifically catalyze 3-O-glucosylation of sapogenins (triterpenoid saponin
backbones), including oleanolic acid and hederagenin.

In the B. vulgaris genome, two quantitative trait loci (QTL) for the four oleanolic
acid-based saponins were found to co-localize with a QTL for flea beetles resistance
(Khakimov et al., 2015; Byrne et al., 2017). The first QTL also co-localizes with LUP5,
the other QTL is syntenic to a region on A. thaliana chromosome 3 containing eight
highly similar CYP72As (Kuzina et al., 2011). Several members of the CYP72A
subfamily from *Glycyrrhiza* and other legumes are involved in oleanolic acid derived
saponin biosynthesis, by oxidizing at C2, C21, C22 and C30 positions (Seki *et al.*, 2011;
Fukushima *et al.*, 2013; Biazzi *et al.*, 2015). These findings, and their location in a QTL
for flea beetle resistance, suggest that CYP72As from *B. vulgaris* may have an
important role in the biosynthesis of hederagenin (C-23 oxidized oleanolic acid) and
derived saponins, and thereby for defense against insect herbivores.

In this study, we identified CYP72A552 from a QTL region involved in flea beetle
resistance, and show that it plays a key role in activating toxicity and/or deterrence
against the devastating agricultural pest diamondback moth (*Plutella xylostella*) and the
tobacco specialist tobacco hornworm (*Manduca sexta*). This key gene in the saponin
biosynthesis evolved through gene duplication, most likely at some time after the origin
of the *Barbarea* genus, and is still under selection.

**Materials and Methods**

**Gene mining and cloning of CYP72A candidate genes from *b. vulgaris***

Putative P450 candidates within the QTLs for flea beetles resistance were searched
using the CLC Workbench (QIAGEN). Eight CYP72A candidate genes were identified
in the QTL region, for which PCR primer pairs (Table S3) were designed either from
genome DNA or cDNA. The full-length sequence of all eight candidate genes was
verified with Sanger sequencing and deposited into the NCBI database with accession
numbers from MH252567 to MH252574. Phylogenies were analyzed as described in
Supplementary Materials and Methods.

**Transient expression in *Nicotiana benthamiana***

For transient expression in tobacco (*N. benthamiana*), the selected genes were amplified
by PCR from *B. vulgaris* cDNA and cloned into the pEAQ-HT-DEST expression vector
(Sainsbury *et al.*, 2009), using USER technology (Nour-Eldin *et al.*, 2010). *Agrobacterium tumefaciens*
infiltration (agro-infiltration) for transient expression in
tobacco leaves was performed as described by Khakimov *et al.*, (2015). After infiltration,
plants were grown for another four-and-a-half days before harvesting for analysis. All
constructs were verified by sequencing.
Expression in yeast

For expression analysis in yeast (*S. cerevisiae*), INVSc1 (ThermoFisher Scientific), *CYP72A552* was cloned into the pYeDP60 vector using USER cloning technology (Nour-Eldin *et al.*., 2010). pYES3-ADH-OSC1 (Seki *et al.*, 2008) and pELC-CYP716A80 was co-transformed with pYeDP60-CYP72A552 constructs, using Frozen-EX Yeast Transformation II™ (Zymo Research). Yeast cells were cultured in synthetic complete medium without uracil, tryptophan or leucine medium containing 2% glucose at 30°C for 24 hours. The cells were then collected and resuspended in synthetic complete medium containing 2% galactose, and cultured at 30 °C for 2 days.

Yeast in vitro microsome assay

Yeast microsome assays were performed as described by Liu *et al.* (2014). 100 µl isolated microsomal, 1 µl substrate (50µM), 100 µl NADPH, 20 µl potassium buffer (1 M, pH7.5), and 278 µl water were mixed and incubated for 1 h at 25 °C with shaking (200 rpm), and the mixture was extracted with 1.5 ml ethyl acetate two times. The combined ethyl acetate extracts were dried with ScanVac prior to GC-MS analysis.

Metabolite analysis by GC-MS and LC-MS

Tobacco leaf discs were ground to fine powder under liquid N₂ with mortar and pestle. 100 mg of powder was used for either GC-MS or LC-MS analysis (Supplementary Materials and Methods). LC-MS data were processed using MetAlign version 4.0 (www.metAlign.nl) as described in Yang *et al.*, (2011) with modifications. MetAlign allowed baseline correction, noise elimination and subsequent spectral data alignment (De Vos et al., 2007). The processing parameters were set to analyze from scan numbers 31-3827 at the retention time of 0.3-32.0 min. The output from MetAlign (signal intensities of each variable) was subjected to an ANOVA to identify metabolites that differed between C1 and C2 with the cutoff value of 2-fold change. Metabolite identification at level 1 and 2, according to the Metabolomics Standards Initiatives (http://www.metabolomics-msi.org/), were assisted by molecular formula, generated from an accurate mass spectrometry data (± 5 ppm), MS/MS fragmentation pattern, and the use of authentic standards.
GC-MS data were processed using DataAnalysis software (version 4.3, Bruker, Germany). Intensities of saponins aglycones, including β-amyrin, oleanolic acid, hederagenin, gypsogenin, and gypsogenic acid, were extracted using characteristic m/z ions including 129, 203, 218, 320, and 471.

Non-choice insect feeding assays
Tobacco hornworm (*Manduca sexta*) and diamondback moth (*Plutella xylostella*) eggs were stored in insect cages in a greenhouse at 26 °C-16 h light : 24°C-8 h darkness, and in a growth room 20 °C-16 h light : 20°C-8 h darkness, respectively, until the larvae hatched. Freshly hatched neonates were placed on tobacco or broccoli (*Brassica oleracea*) overnight for acclimation. First instar larvae of tobacco hornworm and 3rd instar larvae of diamondback moth were starved 4 to 5 hours before used for feeding assays. Non-choice assays were performed as described by Kumar *et al.* (2012) and Augustin *et al.* (2012) with modifications. Briefly, leaf discs (1.57 cm$^2$) from (1) tobacco agro-infiltrated with saponin biosynthetic genes or (2) tobacco and broccoli applied with pure monoglucosides were placed into 24-well plates (15.6 mm well diameter), one leaf disc per well, with three layers of filter paper (Whatman, UK) beneath. 60 µL of water was added on the filter papers to secure humidity. One larva was placed on each leaf disc and fed for 24 to 52 hours. 20 to 30 replicates (larvae) were used for each treatment. Consumed leaf area was measured with a Portable Area Meter (LI-COR Inc., USA) after 24 hours and larval survivorship was assessed after 52 hours.

In vitro synthesis and NMR analysis
Monoglucosides of 3-O-oleanolic acid, 3-O-hederagenin, and 3-O-gypsogenic acid were synthesized by incubating the corresponding aglycon and UDP-glucose with purified UGT73C11 enzymes, as described by Augustin *et al.* (2012). The structures of the *in vitro* produced monoglucosides were verified with either in-house standards or NMR (Supporting Information Materials and Methods).

Sequence evolution analysis
Nucleotide sequences of CYP72As from *B. vulgaris* and *A. thaliana* were aligned on the amino acid level based on codons using MUSCLE and used to construct a
maximum-likelihood bootstrapped phylogenetic tree, using the JTT matrix-based
model (Jones et al., 1992). All the *A. thaliana* P450 sequences were obtained from the
website for *Arabidopsis* cytochrome P450, cytochrome b5, P450 reductase, beta-
glucosidase, and glycosyltransferases (http://www.p450.kvl.dk/) (Paquette et al.,
2000). The tree with the highest log-likelihood (-6728.4268) was selected. The
percentage of trees in which the associated taxa clustered together is shown next to the
branches. Initial tree(s) for the heuristic search were obtained automatically by applying
Neighbor-Join and BioNJ algorithms to a matrix of pairwise distances estimated using
a JTT model, and then selecting the topology with superior log-likelihood value. A
discrete Gamma distribution was used to model evolutionary rate differences among
sites (5 categories (+G, parameter = 1.1865)). The tree was drawn to scale, with branch
lengths measured in the number of substitutions per site. The analysis involved 16
amino acid sequences. The coding data was translated assuming a Standard genetic
code table. There were a total of 522 positions in the final dataset. Evolutionary
analyses were conducted in MEGA7 (Kumar et al., 2016). Nonsynonymous to
synonymous substitution rate ratios (Yang, 2007) were calculated for codon-based
nucleotide alignments with the program ‘codeml’ from the PAML package and PAMLx
(Xu & Yang, 2013). All site-models (NSsites) were tested with model 0 and branch
models 1:b (Hall, 2011).

**Results**

QTL map and genome-based cloning of *BvCYP72As*

A quantitative trait locus (QTL) for oleanolic acid-derived saponins was previously
found to co-localize with a QTL for flea beetles resistance in *B. vulgaris* (Kuzina et al.,
2009). Through fine mapping of this QTL region, a tandem repeat of six *CYP72As* was
identified (Fig. 1b) that is syntenic to a region on *A. thaliana* chromosome 3 containing
a similar tandem repeat of eight *CYP72As*. The remaining two *CYP72As* in the QTL
were placed in *B. vulgaris* contig 4433 and contig 1898. Nucleotide-based sequence
alignment of the *CYP72As* showed that four of the *BvCYP72A* candidate genes share
high nucleotide sequence identity (from 87% to 93%) which may partially explain why
the remaining two *CYP72As* were not assembled in the same position as the rest, as
assembling algorithms do not facilitate assembly of such highly repetitive regions
(Byrne et al., 2017) (Fig. S1). Based on their phylogenetic clustering with CYP72As, three of them were officially named BvCYP72A7, BvCYP72A8, and BvCYP72A9, in agreement with the P450 nomenclature system (http://drnelson.uthsc.edu/cytochromeP450.html). These three CYP72As are considered orthologues to A. thaliana CYP72A7, CYP72A8, and CYP72A9 and accordingly have received the same names as their A. thaliana orthologues. Of the remaining BvCYP72As, one was identified as a pseudogene, named CYP72A561p, and the remaining were named CYP72A552, CYP72A553, CYP72A562, and CYP72A563, respectively.

**CYP72A552 oxidizes oleanolic acid to hederagenin**

To determine which of the BvCYP72A candidates is involved in the biosynthesis of oleanolic acid-derived saponins, each of the seven candidate genes were transiently expressed in tobacco (Nicotiana benthamiana) leaves together with two previously characterized upstream genes in the saponin biosynthesis pathway from B. vulgaris: BvLUP5 and BvCYP716A80 to provide substrates for the CYP72As. We have previously shown that when these two genes are transiently co-expressed in tobacco leaves, oleanolic acid is the major product (Khakimov et al., 2015). When CYP72A552 was co-expressed with BvLUP5 and BvCYP716A80, two major peaks and one minor could be identified (Fig. 2a); this was not found for any of the other CYP72A gene combinations. The two major peaks were identified as hederagenin and gypsogenic acid, and the minor peak as gypsogenin, based on authentic standards. Hederagenin, gypsogenin and gypsogenic acid are the corresponding alcohol, aldehyde and carboxylic acid derivative of oleanolic acid when oxidized at the C-23 position, demonstrating that CYP72A552 oxidizes at this position.

To further verify its catalytic function, CYP72A552 was expressed in yeast cells to enable in vitro microsome enzyme assays. When oleanolic acid was administrated as the substrate to yeast microsomes harboring CYP72A552, only hederagenin was detected (Fig. 2b). We also expressed BvCYP72A552 in yeast cells together with LjOSC1 from Lotus japonicus (which produces mainly β-amyrin), and BvCYP716A80. This resulted in four new peaks (Fig. 2c): hederagenin, gypsogenin, gypsogenic acid,
and 23-hydroxy erthrodiol, the latter putatively identified from the mass spectrum and fragmentation pattern. To determine if the gypsogenin and gypsogenic acid identified from the yeast and tobacco were converted by CYP72A552, hederagenin was administrated as substrate to the microsomes harboring CYP72A552. Hederagenin was in that case not further oxidized, demonstrating that CYP72A552 only oxidizes oleanolic acid to hederagenin (Fig. S2). Thus, CYP72A552 oxidizes oleanolic acid to hederagenin, which is further oxidized to gypsogenin and gypsogenic acid probably by endogenous enzymes in both yeast cells and tobacco plants. In conclusion, of the eight CYP72As in the QTL for flea beetle resistance, only CYP72A552 oxidizes oleanolic acid at the C-23 position to hederagenin (Fig. 2d).

**Hederagenin-based saponins is a major deterrent to both diamondback moth and tobacco hornworm**

The sapogenins (saponin aglycons) from *B. vulgaris* have previously been shown not to affect the tested crucifer herbivores, but only to become a deterrent in their 3-O-glucosylated form(s) (Nielsen *et al.*, 2010; Augustin *et al.*, 2012). To determine the antifeedant activity of C-23 oxidized saponins, the monoglucoside of oleanolic acid (OA), hederagenin (OA alcohol) and gypsogenic acid (OA acid) were synthesized *in vitro* (yielding 18.0, 15.6, and 13.0 mg of each, respectively) and tested for antifeedant activity against the crucifer specialist herbivore diamondback moth (*P. xylostella*), after being purified and structurally verified with in-house standards or by NMR (Fig. 3a, Fig. S3-5, Table S1) as previously described (Augustin *et al.*, 2012). The monoglucosides were applied to broccoli (*Brassica oleracea*) leaf discs at concentrations of 25 and 100 nmol cm\(^{-2}\), and presented to diamondback moth (*P. xylostella*) larvae in non-choice assays. These concentrations where chosen to reflect natural concentrations of hederagenin cellobioside in fresh leaves of *B. vulgaris*, which is approximately 94 nmol cm\(^{-2}\). A dose of 100 nmol cm\(^{-2}\) hederagenin 3-O-monoglucoside reduced larval feeding by 90% compared to controls, which is a four-fold stronger feeding reduction than oleanolic acid 3-O-monoglucoside (Fig. 3b). At the dose of 25 nmol cm\(^{-2}\), only hederagenin 3-O-monoglucoside reduced larval feeding, which is in agreement with the expected dose dependency. Even more strikingly, hederagenin 3-O-monoglucoside caused up to 75% larval mortality, which is 2-fold
higher than that of oleanolic acid 3-O-monoglucoside or gypsogenic acid 3-O-monoglucoside. In conclusion, hederagenin 3-O-monoglucoside is a much stronger defense-component against diamondback moth than oleanolic acid 3-O-monoglucoside or gypsogenic acid 3-O-monoglucoside, and substantiates the role of C-23 hydroxylation in saponin mediated defense.

To develop a fast and efficient test system to evaluate the antifeedant activity of transiently expressed defense compounds in tobacco, effects of the saponins were also tested against larvae of tobacco hornworm (*Manduca sexta*), an important Solanaceous ‘specialist’ herbivore. As done above for broccoli leaf disks, tobacco leaf discs were coated with the three *in vitro* synthesized monoglucosides at the same concentrations as above. At the dose of 100 nmol cm\(^{-2}\), hederagenin 3-O-monoglucoside reduced larval feeding by 88% compared to controls, which is a seven-fold stronger feeding reduction than oleanolic acid 3-O-monoglucoside. Further, hederagenin 3-O-monoglucoside caused 75% larval mortality compared to less than 5% for the other two monoglucosides (Fig. 3). At the dose of 25 nmol cm\(^{-2}\), none of the monoglucosides affected consumption, confirming the dose dependency of saponins for defense. In conclusion, hederagenin 3-O-monoglucoside is a major deterrent or toxin against both diamond back moth and tobacco hornworm. Thus, the system consisting of tobacco leaf discs and tobacco hornworm larvae can be used for structure-activity relationship studies of saponin-mediated plant defense.

**BvCYP72A552 mediates herbivore defense**

Genetic modification, mutants and overexpression lines are not available in *B. vulgaris*, and we therefore analysed further the role of *CYP72A552* in plant defense against insects through transient expression in tobacco leaves. The saponin biosynthesis pathway was first transiently reconstructed in tobacco leaves, which were subsequently presented to the tobacco specialist herbivore, tobacco hornworm (*Manduca sexta*), for bioassays. Two gene combinations, differing with respect to inclusion of *CYP72A552*, were expressed in leaves using agro-infiltration: *LUP5+CYP716A80+UGT73C11* (C1) and *LUP5+CYP716A80+CYP72A552+UGT73C11* (C2) (Fig. 4a). To verify that the pathway was properly reconstituted, the major monoglucosides, as well as sapogenins, were identified in leaf extracts and quantified by LC-MS and GC-MS, respectively (Fig.
When CYP72552 (C2) was co-expressed, hederagenin 3-O-monoglucoside accumulated to 36.6 nmol g\(^{-1}\) FW while concentrations of oleanolic acid 3-O-monoglucoside decreased by 55% compared to C1 to 82.1 nmol g\(^{-1}\) FW. Gypsogenic acid 3-O-monoglucoside accumulated to 109 nmol/g FW in C2, while no gypsogenic acid 3-O-monoglucoside was detected for C1. As for saponin aglycons, the concentration of oleanolic acid decreased by 38% in C2 compared to C1, whereas hederagenin accumulated to 5.8 nmol/g FW in C2 compared to trace amount in C1. These results suggest that both gene combinations performed as expected in tobacco plants and that hederagenin 3-O-monoglucoside only accumulated when CYP72A552 was co-expressed. The results also confirm the presence of enzyme systems in tobacco that metabolize hederagenin further to gypsogenic acid (Fig. 2a), leading to an accumulation of the non-toxic gypsogenic acid 3-O-monoglucoside at the expense of toxic hederagenin 3-O-monoglucoside.

When tobacco leaves with the reconstituted saponin biosynthesis pathway were presented to tobacco hornworm larvae, leaf consumption was significantly reduced for C2 compared to control (15% reduction, p < 0.01; Fig. 4c). In contrast, consumption was not reduced for C1. This suggests that CYP72A552 causes the antifeedant activity of the transiently produced saponins. The relatively low antifeedant activity in the transient expression system relative to when saponins were painted on leaves (above) reflects the low concentration of hederagenin 3-O-monoglucoside (36.6 nmol g\(^{-1}\)) that accumulate in the tobacco leaves. In comparison, B. vulgaris leaves contain approximately ~ 1.400 nmol g\(^{-1}\).

To further determine if the antifeedant effect was directly caused by saponins that accumulated when CYP72A552 was co-infiltrated or if other metabolites might be involved, a non-targeted metabolite analysis comparing C2 to C1 was performed using LC-MS. Analysis of Variance (ANOVA) revealed that 44 mass signals, out of 8491, were significantly upregulated in C2 compared to C1. The 44 mass signals correspond to 15 metabolites, which were further tentatively identified as saponins containing sapogenins with one or two hexoses, including hederagenin 3-O-monoglucoside as verified with an authentic standard (Table S2). This result further substantiates that the
deterrent effect of saponins against tobacco hornworm in tobacco leaves is an effect of CYP72A552.

BvCYP72A552 evolved through gene duplication and selection

A maximum likelihood analysis of CYP72A amino acid sequences from B. vulgaris and A. thaliana was performed to reconstruct their evolutionary history. Fig. 5a (blue marking) indicates that the three orthologous pairs, CYP72A7, CYP72A8, and CYP72A9, evolved before the two species diverged. Subsequently, an ancestral CYP72A duplicated and diverged independently in the two evolutionary lineages leading to A. thaliana and B. vulgaris (Fig. 5a: red marking). Non-synonymous to synonymous substitution ratios (\(\omega = dN/dS\)) were calculated to indicate whether the CYP72As evolved under different selection pressures. PAML analysis showed that the \(\omega\) values of CYP72A552 and CYP72A562 are much higher than for the other CYP72As (Fig. 5a), indicating they have been subject to stronger positive selection, especially in comparison with those evolved before the split of A. thaliana and B. vulgaris.

The order of the CYP72As in the tandem array corresponds well to the topology of the phylogenetic tree, and the order is in agreement with the syntenic tandem array in A. thaliana (Fig. 5b). Each of the three orthologous pairs of B. vulgaris and A. thaliana CYP72As, (CYP72A7, CYP72A8, CYP72A9) are placed at one end of the tandem array in the same (but inverted) order, whereas the three non-orthologous genes (BvCYP72A561P, BvCYP72A562, and BvCYP72A552) are placed in the other end of the tandem array. The bootstrapped tree and \(\omega\) values indicate that BvCYP72A552 evolved through recent gene duplication. In summary, our results suggest that evolution of the saponin-based plant defense in the Barbarea genus was mediated by gene duplications followed by specializing selection.

Discussion

Combined, B. vulgaris G- and P-type plants accumulate up to 49 different saponins structures, as verified by LC-MS-NMR (Khakimov et al., 2016). Some of these saponin structures are more efficient in mediating resistance to insect herbivores than others (Agerbirk et al., 2003; Kuzina et al., 2009; Augustin et al., 2012). Four oleanolic acid-derived saponins from Barbarea vulgaris are known to be constitutively produced and
accumulate upon flea beetle attack (Kuzina et al., 2011; Toneatto et al., 2012), and they have been shown to correlate with flea beetles resistance in a QTL region containing a tandem array of eight CYP72As (Shinoda et al., 2002; Kuzina et al., 2011; Byrne et al., 2017). Here we demonstrate that only one of them, CYP72A552, oxidizes oleanolic acid to its corresponding alcohol, hederagenin, only, and that the monoglucoside of hederagenin is a major deterrent to the crucifer specialist herbivore diamondback moth and the solanaceous facultative ‘specialist’ tobacco hornworm. Transient expression of CYP72A552 in tobacco leaves, together with other known genes in the B. vulgaris saponin pathway, led to accumulation of hederagenin-derived saponins and significantly reduced feeding by tobacco hornworm. Our results indicate that BvCYP72A552 evolved through gene duplication after the split between the A. thaliana and B. vulgaris lineages and is under stronger positive selection than the CYP72As before the split. Collectively, CYP72A552 amplifies the deterrent (or toxic) effect of the oleanolic-based saponins and thus plays an essential role in mediating insect herbivore defense in B. vulgaris.

In previous studies by Fukushima et al. (2013), and Kim et al. (2018), CYP72A68v2 from Medicago truncatula and CYP714E19 from Centella asiatica, respectively, were reported to catalyze up to three consecutive hydroxylations of oleanolic acid at the C-23 position to first hederagenin, then gypsogenin and last gypsogenic acid by one P450. In this study, we show that when CYP72A552 was co-expressed with upstream biosynthesis genes in tobacco leaves or yeast cells hederagenin, gypsogenin, and gypsogenic acid could be detected. However, our in vitro enzyme assay, using isolated yeast microsomes harboring CYP72A552, showed that CYP72A552 exclusively oxidizes oleanolic acid to hederagenin. Thus, we conclude that CYP72A552 oxidizes oleanolic acid at the C-23 position only to hederagenin, and that yeast and tobacco enzymes can further oxidize hederagenin to gypsogenic acid. In agreement with this, Han et al. (2017) found that hederagenin was the only product of yeast microsomes harboring Kalopanax septemlobus CYP72A397 when administrated with oleanolic acid. B. vulgaris, and a few other closely related species, are the only crucifers known to produce saponins (Badenes-Perez et al., 2013). None of the eight syntenic CYP72As located on A. thaliana chromosome 3 could oxidize oleanolic acid to hederagenin or
other compounds (data not shown). Likewise, we have previously shown that *B. vulgaris* has evolved a UDP- glycosyltransferase, UGT73C11, that specifically catalyzes 3-O-glucosylation of sapogenins (Augustin et al., 2012), which does not have a functional homolog in *A. thaliana*. Thus, at least two of the genes involved in the *Barbarea* saponin biosynthesis seem to have evolved and specialized subsequent to their divergence from the *A. thaliana* lineage. In both cases, this seems to have been mediated by gene duplication(s) of biosynthetic genes, initially shared with a common ancestor, followed by positive selection for novel function in the *Barbarea* lineage. In contrast to CYP72A552, neither UGT73C11, CYP716A80 or CYP716A81 are found close to the two QTLs for flea beetle resistance in *B. vulgaris*. This is to be expected, as all saponins are glucosylated at C-3 and most of them carboxylated at C-28, and not all *Barbarea* saponins contribute to resistance. In contrast, only some *B. vulgaris* saponins are hydroxylated at C-23 and among them are the defense-conferring hederagenin-based saponins. We have previously shown that CYP716s and OSCs are promiscuous enzymes (Khakimov et al., 2015), both with respect to substrate and product specificity, and this may explain how *B. vulgaris* with a limited number of genes in the pathway may accumulate up to 49 different saponin structures (Khakimov et al., 2016).

Our study provides important new insight into the structure-activity relationships of saponins, by showing that oxidative modification of the triterpenoid sapogenin may strongly increase or decrease bioactivity. A previous study has shown that a carboxyl group attached to the C-28 of oleanolic acid is crucial for antitumor and hemolytic activity (Carelli et al., 2011; Sui et al., 2017). Here, we showed that adding a hydroxyl group at C-23 significantly decreased feeding and survival of diamondback moth and tobacco hornworm. These results substantiates previous results with the crucifer specialist flea beetle that originally was used to identify the QTLs (Nielsen et al., 2010; Augustin et al., 2012; Christensen et al., 2018).

The actual mode of action of saponins is largely unknown and we can therefore only speculate why the C-23 hydroxy group is so crucial for biological activity. Preliminary analysis of structural changes through molecular energy minimization modelling indicates that the glucose unit at the 3-O position of oleanolic acid monoglucoside is twisted ~ 90 degrees relative to the plane of the sapogenin backbone when a hydroxyl
group is added at position C-23, leading to formation of hederagenin (Fig. S6).

However, when a carboxyl group is introduced instead, the glucose unit is further
twisted to a total ~180 degrees bringing the glucose more or less back to being in the
same plane as the sapogenin backbone. Thus, the presence of the hydroxyl group at C-
23 appears to be crucial for how the C-3 glucose is oriented towards the triterpenoid
backbone, and this may be important for how saponin exert their toxicity at the
molecular level. Saponins are generally believed to disrupt membranes by forming
complexes with membrane sterols or to interact with steroidal receptors (Augustin et
al., 2011). Possibly, the C-23 hydroxylation by CYP72A552 induces a rotation in the
saponin molecule changing its physiochemical properties, and this could possibly
trigger membrane disruption, affinity to steroidal receptors, or decreases efficiency of
saponin detoxifying enzymes in larval guts.

In this study, we introduced a fast and powerful system for determining structure-
activity-relationships of transiently expressed biosynthetic genes in tobacco leaves for
saponin production and subsequent feeding assays with insects. This compliments
traditional feeding studies, where the metabolites are applied to leaf surfaces, by being
more physiologically realistic as the tested compounds are produced and stored within
leaves. The transient system takes less than one-week from introduction of the genes to
insect bioassays can be done, as compared to months needed for stably transformed
plants. Furthermore, the transient expression system allows for production of
compounds that may otherwise be toxic or lethal to the plant if expressed systemically.

An unexpected drawback of the transient tobacco system is that hederagenin was
further metabolized by endogenous tobacco enzymes, hampering the accumulation of
hederagenin-3-O-monoglucoside. Thus, hederagenin 3-O-monoglucoside accumulated
to 36.6 nmol g⁻¹ in the tobacco leaves (corresponding to 2.5 nmol cm⁻²), whereas natural
concentrations in flea beetle resistant B. vulgaris plants is ~ 1.400 nmol g⁻¹
(corresponding to ~96 nmol cm⁻²) and concentrations used in our leaf disk assays were
100 nmol cm⁻². The relatively modest decrease in feeding on transiently saponin-
expressing tobacco (15% reduction), in comparison to the feeding assays with saponin-
painted leaf disks at the high concentration (90% reduction), is most likely due to the
much lower dose of saponins.
In summary, our study provides a key link between CYP72A552 and saponin-mediated plant defense against insects and reveals that its function has evolved through gene duplication and selection for novel function. Our study further highlights evolution of chemical novelties by gene duplication, recruitment of enzymes into new functions, and the importance of chemical modification in plant defense evolution.

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Author contributions

Q.L., T.P.H., and S.B. designed research; Q.L., B.K., and K.R.M. performed research; F.C. and C.E.O. contributed new reagents or analytic tools; Q.L. and B.K. analyzed data; Q.L., T.P.H., and S.B. wrote the paper.

The authors declare no conflict of interest.
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Supporting Information

Additional supporting information may be found in the online version of this article.

Fig. S1. Amino acid sequences alignment of the seven CYP72As from B. vulgaris possible involved in saponin biosynthesis and the eight syntenic A. thaliana CYP72s.

Fig. S2. GC-MS profile of yeast (S. cerevisiae) microsome expressing CYP72A552 administrated with hederagenin (HE).

Fig. S3. Large-scale production of monoglucosides of oleanolic acid (OA), hederagenin (HE), and gypsogenic acid (GA).

Fig. S4. Purification of the monoglucosides of oleanolic acid (OA), hederagenin (HE), and gypsogenic acid (GA).

Fig. S5. Structure of 3-O-monoglucoside gypsogenic acid elucidated by NMR.

Fig. S6. 3D structure of 3-O-oleanolic acid mono-glucoside (a), 3-O-hederagenin mono-glucoside (b), and 3-O-gypsogenic acid mono-glucoside (c).

Table S1. 1D 1H and HSQC based 13C NMR data of 3-O-monoglucoside gypsogenic acid.

Table S2. Tentative identification of metabolites significantly changed between plants transiently expressing the two saponin biosynthetic gene combinations.
a) For Peer Review

hederagenin cellobioside (HEC)
oleanolic acid cellobioside (OAC)
gypsogenin cellobioside (GEC)
4-epi hederagenin cellobioside (EHC)

\[
\text{R}_1 \quad \text{R}_2 \\
\text{CH}_2\text{OH} \quad \text{CH}_3 \\
\text{CH}_3 \quad \text{CH}_3 \\
\text{CHO} \quad \text{CH}_3 \\
\text{CH}_3 \quad \text{CH}_2\text{OH}
\]

b) SSR marker

Pseudomolecule 7

Manuscript submitted to New Phytologist for review
Gene combination

C1  LUP5+CYP716A80+UGT73C11
C2  LUP5+CYP716A80+CYP72A552+UGT73C11
Control (CK)  Empty vector