RNAi-mediated endogene silencing in strawberry fruit: detection of primary and secondary siRNAs by deep sequencing

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Introduction

Eukaryotic organisms, including plants, animals and fungi, have developed a double-stranded RNA (dsRNA)-induced gene silencing mechanism to protect their cells against invading nucleic acids (Brodersen and Voinnet, 2006). In this RNA interference (RNAi) pathway, dsRNA is specifically and rapidly degraded into small interfering RNAs (siRNAs) of 21 to 25 nucleotides (nt) by RNase III-like enzymes, known as Dicer-like proteins (DCL; Eamen et al., 2008; Mlotshwa et al., 2008). The siRNAs are incorporated into the RNA-induced silencing complex (RISC), which eventually leads to the degradation of any complementary single-stranded RNA in the cytoplasm. In addition, siRNAs are recruited into RNA-induced initiation of the transcriptional silencing complex (RTS) causing chromatin modifications (Noma et al., 2004). Foldback of self-complimentary intron-hairpin sequences (ihp), hybridization of sense and antisense sequences and the action of an RNA-dependent RNA polymerase (RdRP) can give rise to dsRNA from endogenous, viral and transgenic RNA molecules. Studies have shown that RNAi is implicated in the suppression of transposon activity, resistance to viral infection, post-transcriptional and post-translational regulation of gene expression, and the epigenetic regulation of chromatin structure (Kusaba, 2004; Wang and Metzlaff, 2005).

RNAi has attracted great attention as a reverse genetic tool for studies of gene function in numerous organisms (Gilchrist and Haughn, 2010; Hoffmann et al., 2006; Lipardi et al., 2003; Zhai et al., 2009). The sequence specificity of RNAi-mediated gene inactivation allows silencing of individual genes as well as multiple members of a multigene family (Miki et al., 2005). Transitivity, the spread of RNA silencing along primary target sequences, is an aspect of RNAi that has not been well understood (Bleys et al., 2006). Endogene-derived mRNAs can become a production source of secondary siRNAs that correspond to regions of the target gene outside the original trigger (Sanders et al., 2002; Sijen et al., 2001). Secondary siRNA itself can trigger degradation of homologous transcripts through a process called transitive silencing. The production of secondary siRNAs from regions outside of the sequence initially targeted by primary siRNAs was first described in Caenorhabditis elegans where it proceeds over a distance of a few hundred nucleotides in the 3′→5′ direction (Sijen et al., 2001).

In plants, spreading of the RNAi signal has been shown to occur in both the 3′→5′ and the 5′→3′ directions along transgene RNAs in a primer-dependent and primer-independent manner (Bleys et al., 2006; Braunstein et al., 2002; Himber et al., 2003; Klahre et al., 2002; Košciarška et al., 2005; Miki et al., 2005; Petersen and Albrechtsen, 2005; Vaistij et al., 2002; Van Houdt et al., 2003). Silencing induced by 3′ fragments spread only for a limited distance of up to 332 nt, with a possible limit of 600 nt, while gene silencing in the 5′→3′ direction has been shown to spread over a distance of at least 1000 nt (Petersen and Albrechtsen, 2005; Vaistij et al., 2002). Although transitive RNA silencing of transgenes has been clearly demonstrated, many
studies failed to prove transitivity along endogenous sequences. It was assumed that endogenous sequences are resistant to transitivity by some inherent properties (Vaistij et al., 2002; Himber et al., 2003; Kościarska et al., 2005; Miki et al., 2005; Petersen and Albrechtsen, 2005).

In plants, animals and fungi, RdRPs have been proposed to be a part of the RNAi silencing system (Schwach et al., 2005). Their likely biochemical role is the production of dsRNA, which is consistent with the in vitro activity of RdRPs from Lycopersicum esculentum (Schiebel 1998), Neurospora crassa (Makeyev and Bamford, 2002) and Schizosaccharomyces pombe (Motamedi et al., 2004). Models of transitive silencing suggest that RdRPs utilize siRNAs as primers and homologous transcripts as template for dsRNA synthesis (Alder et al., 2003; Sijen et al., 2001). The reaction amplifies the silencing response and mediates the production of secondary siRNAs. RdRPs add ribonucleotides to the 3′ end of a growing RNA chain, which would explain spreading of the silencing in the 3′–5′ direction along the target transcript. The 5′–3′ spreading of the silencing signal can be explained by RdRP-mediated unprimed dsRNA synthesis at the 3′ end of target mRNAs and/or by siRNA-directed dsRNA synthesis using an antisense transcript as template (Baulcombe, 2004; Vaistij et al., 2002).

In this paper, we describe the down-regulation and the spread of silencing of two endogenous strawberry genes Fragaria × ananassa chalcone synthase (FaCHS; Lunkenbein et al., 2006a) and F. × ananassa O-methyltransferase (FaOMT; Wein et al., 2002) by ihp constructs and transitive RNAi vectors. To systematically investigate the sequence dependency of RNAi directed to FaOMT and FaCHS, we prepared ihp constructs harbouring sequence fragments (219–303 bp) along the full lengths of both target genes. All sequence fragments resulted in a significant down-regulation of the respective gene expression. The spreading of the silencing signal could be demonstrated by agroinfiltration of transitive RNAi vectors and was confirmed by deep sequencing of small RNAs. The data suggest that both direct ihp and transitive methods are useful tools in plant functional genomics and biotechnology, but homologous ihp sequences are superior due to their silencing efficacy, which was also demonstrated by the abundance of primary siRNAs in comparison with secondary siRNAs.

**Results**

Efficient silencing of FaOMT and FaCHS is independent of the sequence fragments used in the ihp construct

RNA silencing with an ihp construct (pBI-FaCHSsi) containing a 303-bp-long sense and antisense sequence of FaCHS separated by a Fragaria intron sequence has been used to suppress chalcone synthase activity in strawberry (Fragaria × ananassa) fruit, resulting in a significantly reduced level of red fruit pigments (Hoffmann et al., 2006). Here, we tested the general applicability of ihp constructs to silence endogenous genes in fruits of the nonmodel strawberry plant and systematically analysed the outcome of the silencing technique, to devise a method for the application of RNAi to high-throughput plant functional genomics in this species. In addition to FaCHS, the flavour-related FaOMT gene (AF220491; Wein et al., 2002; Zorrilla-Fontanesi et al., 2012) was chosen. Repression of FaOMT transcripts led to a near total loss of 2,5-dimethyl-4-methoxy-3(2H)-furanone (DMMF), the product formed by the encoded enzyme from the substrate 4-hydroxy-2,5-dimethyl-3(2H)-furanone (HDMF). In addition, lower levels of feruloyl glucose in comparison with caffeoyl glucose were observed (Lunkenbein et al., 2006a,b). Since it has been shown that the potency of siRNAs can vary drastically due to their thermodynamic properties, and that complex target structures may affect the activity of siRNAs (Kurreck, 2006; Overhoff et al., 2005; Schubert et al., 2005), we systematically investigated the efficiency of RNAi-mediated gene silencing by different ihp constructs covering the complete ORFs of FaOMT and FaCHS. Both gene sequences were divided into five (A to E) overlapping fragments (Figures 1-3). These fragments were used for the assembly of the ihp constructs pbI-FaOMT_A1 to Ei and pBI-FaCHS_A1 to Ei. Subsequently, they were agroinfiltrated into ripening strawberry fruits, together with the control vector pbI-Intron (Figure 1). Quantitative PCR was applied to assess the efficacy of target gene silencing (Figures 2 and 3). The relative expression levels of FaOMT and FaCHS in native versus pbI-Intron treated fruit were statistically not significant (\( P = 7.2 \times 10^{-1} \) and \( P = 5.7 \times 10^{-1} \)), indicating that injection of the control construct did not alter the expression of the target genes. However, agroinfiltration of ihp constructs resulted in a significant (\( P < 1.0 \times 10^{-2} \)) reduction in the transcript levels of FaOMT (Figure 2) and FaCHS (Figure 3) by more than 80% (relative gene expression < 0.2) in comparison with the levels in untreated fruits, with the exception of pbI-FaCHS_A1. Although the median for pbI-FaCHS_A1 is less than 0.2 (reduction by more than 80%), the \( P \)-value is slightly higher than 1.0 \( \times 10^{-2} \) due to the high variance of the values. The uneven distribution of the A. tumefaciens strains in the tissue is an inherent problem of the agroinfiltration technique and causes high variation of the expression level. The data indicate that all five sequences comprising 240 up to 303 nt of both genes can act as efficient inducers as well as targets of post-transcriptional silencing.
Efficient RNA silencing manifests itself in altered metabolite levels

Because FaCHS encodes an essential enzyme in the anthocyanin biosynthetic pathway, the reduction in FaCHS transcript levels results in a loss of pigmentation in infected fruits compared to control fruits. All five ihp constructs produced a similar chimeric phenotype, indicating a significant reduction in pelargonidin 3-O-glucoside (Figure 4). This was confirmed by LC-MS analyses (data not shown). In contrast, down-regulation of FaOMT by pBI-FaOMT_Ai to Ei did not yield an altered visible phenotype. However, LC-MS analysis revealed differences in the ratio of HDMF to the total amount of furanones (DMMF and HDMF). Strawberries agroinfiltrated with ihp constructs targeted to FaCHS_Ei produced significantly lower levels (P < 1.0 E-2) of the methylated product DMMF as compared with the substrate HDMF, resulting in a higher proportion of HDMF relative to the total amount of furanones (Figure 5, top). All five constructs used
were similarly effective. The normalized levels of HDMF in the fruit expressing pBI-Intron were not significantly different from the levels in untreated fruit ($P = 6.4 \ E^{-1}$).

The normalized levels of feruloyl glucose another potential product formed by FaOMT in fruit were not affected by agroinfiltration of pBI-FaOMT_Ai to Ei when compared to the levels in untreated and pBI-Intron infiltrated fruit (Figure 5, bottom). However, statistical analysis revealed a significant difference ($P = 3.0 \ E\^{-3}$) between the normalized level in untreated and pBI-Intron control fruit, indicating an induction of the phenylpropanoid biosynthesis by agroinfiltration. The increased formation of phenylpropanoic acids probably counters the metabolic effects of FaOMT silencing on the levels of the phenolic acids.

Transitive silencing with transcriptional fusion of GUS ihp and a partial sequence of FaCHS

We assembled two constructs (Figure 1) to probe whether the RNA silencing activity of a silencing inducer RNA can be transmitted to the sequence of an endogenous strawberry gene (secondary target) by fusing part of this sequence to the silencing-inducing sequence in a single transcript (primary target; Bleys et al., 2006). One nucleotide sequence represented a silencing inducer and the other a primary target. A construct carrying an ihp of a partial GUS sequence (pBI-GUSi) was used as source of primary siRNAs, while a fusion of the homologous GUS sequence with a FaCHS fragment (pBI-CHS-GUS) served as primary target (Van Houdt et al., 2003). T-DNAs were introduced into ripening strawberry fruit by agroinfiltration 14 days after pollination. Strawberries harvested in the full ripe stage showed the typical chimeric phenotype of FaCHS deficient fruits but did not feature

Figure 4 Phenotypes of untreated strawberry fruit and fruit agroinfiltrated with pBI-FaCHS_Ai to pBI-FaCHS_Ei.

Figure 5 Metabolite analyses. Normalized levels of HDMF (top left) and caffeoyl glucose (bottom left) in native untreated strawberry fruit and fruit infiltrated with pBI-Intron and ihp constructs FaOMT_Ai to FaOMT_Ei (A–E) calculated as ratio of HDMF to the total concentration of HDMF and DMMF and as ratio of caffeoyl glucose to the total concentration of caffeoyl glucose and feruloyl glucose. Number of biological replicates: native untreated fruit ($N = 22$), pBI-Intron ($N = 26$), A ($N = 22$), B ($N = 23$), C ($N = 21$), D ($N = 21$), E ($N = 23$). The Wilcoxon–Mann–Whitney U-test was used to assess intergroup significance (top right and bottom right). Statistically significant differences ($P < 1.0 \ E^{-2}$) are shown in bold.

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the extensive white sections as seen with fruit agroinfiltrated with FaCHS ihp constructs (data not shown). LC-MS analysis confirmed that the levels of pelargonidin derivatives were not as strongly suppressed by transitive silencing as by ihp constructs of FaCHS sequences (Figure 6). In a control experiment, only the FaCHS-GUS construct was agroinfiltrated but without pBI-GUSi. The result clarified that the silencing effect is caused by transitive silencing and not by FaCHS-GUS-induced sense cosuppression as infiltration of FaCHS-GUS does not affect the pigmentation of strawberry fruit (Figure S1). It appears that transitive silencing of the endogenous FaCHS gene(s) by chimeric recombinant GUS-CHS fusions, together with the inducer pBI-GUSi, is less efficient than the down-regulation by ihp constructs targeting directly FaCHS sequences.

Discussion

We have exploited RNAi as a reverse genetic tool to develop a rapid system to perform functional genomics in strawberry fruit (F. × ananassa) (Griesser et al., 2008; Hoffmann et al., 2006; Matthew, 2004; Song et al., 2015). To systematically investigate the silencing efficacy of ihp constructs that carry different gene sequence segments, we divided the ORFs of FaCHS and FaOMT into five fragments (240–293 nt). In total, ten vectors were assembled each containing the nucleotide sequence of one fragment in sense and corresponding antisense orientation separated by an intron obtained from a F. × ananassa quinone oxidoreductase gene. Bioinformatic analysis of the modelled mRNA structures suggested different silencing efficiencies of the sequences A to E due to strongly varying theoretical accessibilities (ranging from 0.48 to 1.90 for FaOMT fragments and 0.05 to 1.88 for FaCHS fragments) of local target sites as has been reported by Schubert et al., 2005.. Accessible local target sites are defined as mRNA regions with more than 10 unpaired nt (Overhoff et al., 2005). However, the efficiencies of the applied constructs to silence the endogenous FaCHS and FaOMT genes did not show significant differences. Thus, it appears that additional factors govern the efficiency of the post-transcriptional silencing process in plant cells. Until now, all characterized siRNAs get incorporated into ARGONAUTE (AGO) proteins to contribute to RISC formation (Fang and Qi, 2016). Recently, it was suggested that subcellular compartmentalization of AGO-miRNA-RISC complexes and sequestration of miRNAs and siRNAs could be additional factors determining the silencing efficiency (Fang and Qi, 2016; Wu et al., 2015).

Although our results did not show any significant difference in the silencing efficiency of the various constructs, the uneven distribution of primary siRNAs along the target sequence (Figure 7), that is the detection of siRNA hotspots and low-abundant siRNAs, suggests that the use of shorter inducer sequence would eventually lead to unequal silencing efficacies. As the distance between siRNA hotspots is less than 200 nt inducer, sequences of more than 200 nt in length are sufficient to initiate the stable down-regulation of endogenous genes.

Quantitative PCR analyses with primer pairs specific to the 5’ regions of the target RNAs (located in FaOMT fragment A to B and FaCHS fragment B to C) revealed substantial degradation of primer target sites after agroinfiltration of all ihp RNA sequences.
used (Figures 2 and 3). Degradation of mRNA outside the primary RNAi target sites might be explained by digestion of the aberrant mRNA with exonucleases such as XRN4 (Vazquez and Hohn, 2013). Alternatively, this observation might provide a hint of the spreading of the RNAi signal from the 3' to the 5' region over a distance of up to 1000 nt and in the reverse direction of up to 500 nt. Spreading over a distance of at least 1000 nt from the 5' end to the 3' end has been shown by virus-induced gene silencing (VIGS), while 3'–5' spreading extended at least through 332 nt, with a possible limit of 600 nt (Petersen and Albrechtsen, 2005; Vaistij et al., 2002). Thus, agroinfiltration of ihp constructs appears to be equally effective in spreading of the RNAi signal as VIGS.

It has been proposed that the interaction of sense transcripts with the antisense siRNAs might change the structure of the RNA or of a ribonucleoprotein complex and thereby allow RdRP to access the 3' end of the target RNA. Synthesis of dsRNA from the 3' end would result in siRNA production corresponding to the entire transcript sequence and could explain RdRP-mediated spreading in a primer-independent way (Vaistij et al., 2002).

There are only a few reports showing the spread of RNAi along endogenous genes as we have shown by agroinfiltration of transitive vectors into strawberry fruit (Figure 6). By contrast, transitivity has frequently been observed along reporter transgenes (Sanders et al., 2002). Since most studies failed to demonstrate spreading along endogenous plant genes, it has been concluded that transgenes, and not endogenous genes, are good templates for generation of secondary siRNAs. Reasons for the plant RdRP's apparent preference for the transgene transcripts as a template in the transitivity remained unclear (Miki et al., 2005; Petersen and Albrechtsen, 2005; Shimamura et al., 2007; Vaistij et al., 2002). Transgenes and RNAi probes are mostly expressed under the control of strong promoters (e.g. CaMV 35S). Thus, the primary silencing inducer targeting the transgene gives rise to a
large number of primary siRNAs that eventually exceed a critical threshold level, which may lead to the activation of RdRP, and finally to efficient transitive silencing. Consistent with this hypothesis, it has been shown that a hairpin construct controlled by the strong 35S promoter induced a stronger silencing phenotype than the same construct controlled by the weak nopaline synthase promoter (Chuang and Meyerowitz, 2000). In addition, the efficiency of transitive silencing of endogenes depends on the degree of sequence homology to the primary target (Bleys et al., 2006). However, strong silencing of the target RNA would mean that the template RNA for RdRP is scarce, which would also reduce the efficiency of spreading (Vaistij et al., 2002). Taken together, both the level of siRNAs and the target transcript might determine the onset of transitivity. Transcript levels of numerous endogenous genes are less abundant and therefore less prone to transitive silencing (Vaistij et al., 2002).

Attempts at explaining the absence of RNA silencing of the phytoene desaturase (PDS) endogenous gene have evoked the characteristics of endogenous RNAs that inhibit RdRP or prevent interactions with siRNAs (Vaistij et al., 2002). However, in the meantime, PDS alleles have been successfully down-regulated by a hairpin construct in sugarcane and tobacco, which invalidates the former hypothesis (Osabe et al., 2009; Wang et al., 2010). Thus, the assumption that transgenes are better templates for production of secondary siRNAs is no longer considered a likely explanation for the inability to detect transitivity in certain studies. Our results support the hypothesis that there is no principle distinction between transgenes and endogenous genes, except their promoters with respect to their active recruitment in RNA silencing including spreading of the signal (Sanders et al., 2002).

In Arabidopsis, it has been shown that both transgenes and endogenes can be silenced by secondary transitive signals (Bleys et al., 2006). Since insertion of additional nt sequences between the region targeted by the silencing inducer and the upstream region homologous to a transgenic target (GUS) led to a delay of the onset of transitive silencing, it has been suggested that transitivity requires time to accumulate a certain steady state level of secondary siRNAs that results in a corresponding maximum plateau level of silencing. Thus, ihp constructs driven by a strong promoter will reach the level earlier.

RNA silencing was discovered in plants as a mechanism whereby invading nucleic acids such as viruses are suppressed. In this context, it appears logical that transgenes that are expressed under the control of viral promoters (e.g. CaMV 35S) are efficiently silenced by transitive RNAi, while endogenous transcripts seem to be protected (Bleys et al., 2006). This observation supports the proposed biological function of this process as a natural antiviral response. Spreading of the RNAi signal by transitive silencing even intensifies the efficacy of viral gene suppression. However, it could also lead to uncontrollable degradation of plant genes that show partial homology to the inducer sequence. In strawberry, the introduction of the Vitis vinifera stilbene synthase gene under the control of the 35S promoter inadvertently caused the down-regulation of the endogenous chalcone synthase gene transcripts, probably due to transitive silencing (Hanhineva et al., 2009).

To detect primary and secondary siRNAs and to clearly prove the spreading of the RNAi signal, deep sequencing of small RNAs in FaOMT_Ci and FaOMTi fruits was performed for the first time in strawberry fruit and revealed 21, 22 and 24 nt small RNAs (Figure 7d) as the most dominant sizes, consistent with the siRNA size distribution observed in angiosperms (Chávez Montes et al., 2014). The high percentage of 21nt RNAs indicated that they were predominantly produced by the activity of DCL4-like nucleases (Fusaro et al., 2006). DCL2 and DCL3 can substitute DCL4, producing 22nt and 24nt RNAs (Ghildiyal and Zamore, 2009; Small, 2007). In plants, AGO proteins sort miRNAs and siRNAs based on size and the identity of the 5′ nucleotide. 21mers typically associate with AGO1 and guide mRNA cleavage and subsequent secondary siRNA production, whereas 24mers associate with AGO6 promoting the formation of repressive chromatin (Ghildiyal and Zamore, 2009). Furthermore, it has been shown that also 22nt miRNAs can trigger siRNA production, but apparently asymmetrically positioned bulged bases in the miRNA-miRNA* duplex within the AGO proteins are sufficient to trigger transitivity (Manavella et al., 2012). When only small RNAs were considered that mapped into their target sequence (FaOMT_Ci and FaOMTi), a marked reduction of the proportion of long RNAs (>25 nt) was observed but a substantial number of short RNAs (<21 nt) were still counted (Figure S2). Interestingly, 9.5% and 9% of the siRNAs isolated from FaOMT_Ci and FaOMTi fruits, respectively, targeted the FaOMT sequence. Thus, the RNAi machinery was efficiently recruited by the ihp vectors. The proportion of long RNAs (>21 nt) was increased in FaOMTi fruits in comparison with FaOMT_Ci samples, whereas the percentage of short RNAs (<21 nt) was higher in FaOMT_Ci fruit. The reason for this observation is unclear, but the very short RNAs might be secondary degradation products of siRNAs.

Clustering of siRNAs along the inducer sequences was observed, indicating that siRNAs are apparently nonrandomly distributed (Figure 7). Similar asymmetry in siRNA distribution has been observed in studies on the RNAi-mediated silencing of the GFP gene (Llave et al., 2002) and plant virus-induced RNA silencing (Molnár et al., 2005). One explanation is that loading of siRNAs into AGO proteins, which are part of the RISC complex, is specified by the 5′ terminal nucleotide as most 21 nt siRNAs with 5′ terminal U are predominantly associated with AGO (Mi et al., 2008). Secondly, it was shown that the position of transacting siRNA-generating loci (TAS genes) can restrict siRNA production to certain regions (Rajeswaran et al., 2012). Also the distinctive distribution pattern of mapped short sequences in FaOMT_Ci and FaOMTi infiltrated fruits indicates certain hotspots of siRNA production (Figure 7c and d).

Primary siRNAs were identified by mapping to the inducer sequence, whereas secondary siRNAs are produced from regions outside of the sequence initially targeted by primary siRNAs. Low-abundant secondary siRNAs were detected upstream and in particular downstream of the inducer sequences (Figure 7c insets) indicating that formation by primer-independent synthesis by RdRP strongly prevails. The low numbers of small RNAs upstream of the inducer sequence make transitive silencing by siRNA-primed cRNA synthesis very unlikely. Similarly, silencing induced by a central B-glucuronidase (GUS) gene fragment in Nicotiana benthamiana carrying a GUS transgene spread only into downstream regions (Petersen and Albrechtsen, 2005), and secondary siRNAs originated preferentially from the 3′ region of the inducer region in tobacco (Shimamura et al., 2007). However, in Caenorhabditis elegans, it has been shown that secondary siRNA has a 5′ triphosphate, precluding cloning methods that rely on a single 5′ phosphate (Miska and Ahringer, 2007). Thus, this species might be underrepresented in the large-scale sequencing studies. Di- and triphosphate groups at the 5′ termini of secondary siRNAs.
also indicate that they are likely to be primary, unprimed RdRP products (Carthew and Sontheimer, 2009).

The strong but similar sense/antisense bias of primary and secondary siRNAs (Figure 7d) suggests a related formation pathway. It is conceivable that secondary siRNAs are also formed by DCL4 3’ of the primary targeted FaOMT, as mRNA cleavage, rather than priming of RdRP by primary siRNAs, was proposed as the signal for siRNA amplification (Ghildiyal and Zamore, 2009).

Overall, in our study, primary siRNAs were three orders of magnitude more abundant than secondary siRNAs (Figure 7) confirming the observation that ihp constructs, compared with the transitive construct, generated higher frequencies (data not shown) and efficacies of loss-of-function phenotypes (Filichkin et al., 2007; Figure 6).

Our results demonstrate that endogenous genes can be efficiently down-regulated in strawberry fruit by RNAi-mediated silencing after agroinfiltration of ihp constructs carrying sequences of 200 up 300 nt homologous to an endogene within 14 days. Transitive vectors are less effective probably due to lower levels of secondary siRNAs targeting the gene of interest. Since the silencing efficiency is independent of the calculated theoretical accessibility of the nucleotide sequences used, and thus independent of the gene fragment, the method represents a versatile tool to perform functional genomics research in strawberry.

Materials and methods

Constructs

The pBI-Intron control construct was assembled as described by Hoffmann et al. (2006). pBI-Intron contained GUS separated by the first intron of the F. × ananassa quinine oxidoreductase gene (AY158836, nucleotides 4107–4561). The assay constructs were made by using pBI121 (Jefferson, 1987). The second intron of the F. × ananassa quinine oxidoreductase gene (AY158836, nucleotides 4886–4993) was PCR-amplified from strawberry F. × ananassa cv. Elsanta genomic DNA and cloned into BamHI–EcoRI cut pBI121 to replace GUS. For cloning of the FaCHS and FaOMT silencing constructs, the genes were divided into five parts, respectively, that overlapped each other to ensure complete coverage of the full sequences (Figures 2 and 3). These parts were PCR-amplified by primers introducing restriction sites allowing the formation of self-complementary ihp structures. The resulting plasmids were named pBIFaCHS_Ai to pBIFaCHS_Ei and pBIFaOMT_Ai to pBIFaOMT_Ei. To generate pBI-GUSi, a 414-bp fragment of GUS (AF485783) was inserted into the 5′ and 3′ arms of the intron in sense and antisense direction allowing the formation of self-complementary ihp structures. The resulting plasmids were named pBIFI795154) and FaOMT (AF220491) transcripts was performed using the Actin gene (AB116565) from F. × ananassa as a reference (Almeida et al., 2007). Quantitative PCR primers can be found in Table S1, with supplemental information about amplicon lengths and positions.

All reactions were run two times with two sets of cDNAs. The specificity of the PCR amplification was checked with a melting curve analysis following the final step of the PCR. For each sample, threshold cycles (Ct, cycle at which the increase of fluorescence exceeded the threshold setting) were determined. Relative gene expression data were normalized to the mean expression of FaOMT (n = 17) and FaCHS (n = 23) in native, untreated fruits (set to 1). The relative expression ratio was calculated according to Pfaffl (2001).

Metabolite analysis

Identification and quantification of strawberry fruit metabolites were performed by liquid chromatography-UV-electrospray ionization-mass spectrometry (LC-MS) as described by Hoffmann et al. (2006) and Grießner et al. (2008). Box plots of signal intensities were generated by Sigma Plot (SPSS, Chicago, IL), and statistical significance levels were calculated using the Wilcoxon–Mann–Whitney U-test (Hart, 2001).

Bioinformatic analysis and processing of transcriptomic data

PBI-FaOMTii and pBI-FaOMT_Cii were agroinfiltrated into ripening strawberry fruit according to Hoffmann et al. (2006). Total RNA was extracted from mature fruit using the CTAB extraction procedure (Asif et al., 2000; Liao et al., 2004). The RNA samples were treated with RNase-free DNase I (Fermentas, St. Leon-Rot, Germany) for 1 h at 37 °C. First-strand cDNA synthesis was performed in duplicate in a 20 µL reaction volume, with 1 µg of total RNA as the template, random primer (random hexamer, 100 pmol) and M-MLV reverse transcriptase (200 U, Invitrogen, Karlsruhe, Germany) according to the manufacturer’s instructions. Real-time PCR was performed with 2 µL of cDNA on a StepOnePlus System (Applied Biosystems, Foster City, CA) using SYBR Green PCR Master MIX (Applied Biosystems). To monitor dsDNA synthesis, data were analysed with ABI StepOne Software v2.0. Relative quantification of the FaCHS (AI795154) and FaOMT (AF220491) transcripts was performed using the Actin gene (AB116565) from F. × ananassa as a reference (Almeida et al., 2007). Quantitative PCR primers can be found in Table S1, with supplemental information about amplicon lengths and positions.

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RTA 1.12.4.2, CASAVA 1.7.0 and OLB-1.9.0 (all Illumina Inc.). Prior to read sorting, the 3′ adaptor sequence was trimmed from the raw reads using cutadapt 0.9.3 (Martin, 2011). Sequencing (~50 nt) yielded 14 288 304 reads (OMT_short) and 21 722 563 reads (OMT_long), respectively.

Subsequent data processing was performed on the Galaxy server (Blankenberg et al., 2010b; Giardine et al., 2005; Goecks et al., 2010). The application programming interface (API) was used to set up pipeline analyses (Sloggett et al., 2013), and the Galaxy Data Manager was employed for handling built-in reference data (Blankenberg et al., 2014a). Tools were installed and maintained via Galaxy Tool Shed (Blankenberg et al., 2014b). Before mapping, reads were filtered according to their quality score and length (15–50 nt; min. quality 20) with the fastq_filter v. 1.0.0 tool implemented in Galaxy (Blankenberg et al., 2010a). Overall read quality was tracked with the FastQC software by S. Andrews (http://www.bioinformatics.babraham.ac.uk/projects/fastqc/).

After quality clipping, 11 693 897 (81.84% of total reads, OMT_short) and 17 084 937 (78.65%, of total reads OMT_long) reads were subjected to the mapping against the F. vesca reference genome (version 2.0.a1: downloaded from Genome Database for Rosaceae GDR www.rosaceae.org; Tennesen et al., 2014). Mapping was done by TopHat read aligner v 2.0.14 (Kim et al., 2013) for single-end data in default settings. Aligned reads were counted from resulting bam files by HTSeq-count v. 0.6.0 (Anders et al., 2015) in “Union” mode for stranded reads with a minimum alignment quality of 10. The gene prediction input file was also downloaded from GDR (Tennesen et al., 2014). The coverage of small RNAs was visualized with the Integrated Genomics Viewer (Igv, Robinson et al., 2011).

Modelling of mRNA structures

Modelling of the FaCHS_Ai to Ei and FaOMT_Ai to Ei mRNA structures and calculation of the theoretical accessibilities was carried out online via the Mfold web server for nucleic acid folding and hybridization prediction (http://unafold.rna.albany.edu) in default parameters as published by Zuker (2003).

Acknowledgements

We thank Robert Kurtzer and Hannelore Meckl for technical assistance.

Conflict of interest

The author(s) declare that they have no competing interests.

Funding

This work was supported by the DFG (grant no. SCHW634/10-2, SCHW634/24-1) and BMBF (grant no. PLANT-KBBE, FraGENOMICS, 0315463).

References

Endogene silencing in strawberry fruit


furanone, one of the key aroma compounds in strawberry fruits. *Plant J.* 31, 755–765.


**Supporting information**

Additional Supporting information may be found online in the supporting information tab for this article:

**Figure S1** Control experiments. Infiltration of pBI-FaCHS-GUS to verify that the chimeric effect is caused by transitive silencing, and not by FaCHS-GUS-induced sensed co-suppression (right). Successful down-regulation of CHS as demonstrated by the partial loss of pigmentation was shown by agroinfiltration of a pBI-FaCHSi construct (left).

**Figure S2** Size distribution of total genome-wide short RNAs (a), short RNAs mapped in the FaOMT_Ci and FaOMTi target region (b), and short RNAs mapped outside of the target regions but within the full length FaOMT sequence (c). Relative proportions of short RNA sequences are shown as percentages for each size category.

**Table S1** Primer sequences used for the cloning and quantification of the different FaCHS and FaOMT fragments, including the length of the amplicons in nucleotides (nt), and their positions on the respective genes. Restriction sites are denoted in bold letters.