Ectopic Expression of a Maize Hybrid Down-Regulated Gene ZmARF25 Decreases Organ Size by Affecting Cellular Proliferation in Arabidopsis

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Abstract

Heterosis is associated with differential gene expression between hybrids and their parental lines, and the genes involved in cell proliferation played important roles. AtARF2 is a general cell proliferation repressor in Arabidopsis. In our previous study, two homologues (ZmARF10 and ZmARF25) of AtARF2 were identified in maize, but their relationship with heterosis was not elucidated. Here, the expression patterns of ZmARF10 and ZmARF25 in seedling leaves of maize hybrids and their parental lines were analyzed. The results of qRT-PCR exhibited that ZmARF25 was down-regulated in leaf basal region of hybrids. Moreover, overexpression of ZmARF25 led to reduced organ size in Arabidopsis, which was mainly due to the decrease in cell number, not cell size. In addition, the cell proliferation related genes A1ANT, AtGIF1 and AtGRF5 were down-regulated in 35S::ZmARF25 transgenic lines. Collectively, we proposed that the down-regulation of ZmARF25 in maize hybrid may accelerate cell proliferation and promote leaf development, which, in turn, contributes to the observed leaf size heterosis in maize.

Introduction

Heterosis is defined as advantageous quantitative and qualitative traits of offspring over their parents, and the utilization of heterosis principles has been a major practice for increasing productivity of plants and animals [1]. In spite of its importance and successful application, the underlying molecular mechanism for heterosis is still needs to be elucidated [2–5]. Studies on plant form evolution suggest that phenotype evolution often proceeds through changes in the spatial and temporal patterns of gene expression [6]. Theoretically, all the genes in hybrid are inherited from its two parental lines, but hybrid performance or phenotype can be quite different from its parents, thereby, demonstrating heterosis [7,8]. Therefore, the alteration of gene expression in hybrids may be responsible for hybrid vigor [4,8]. Up to date, genome wide gene expression profiles of different organs or tissues between hybrids and their parents in plants have been analyzed [9–15], and all possible modes of gene action were observed, including additivity, high- and low-parent dominance, underdominance, and overdominance [9–15]. To gain further insight into the possible roles of differentially expressed genes between hybrid and its parental lines in plant development and heterosis, the functions of some differentially expressed genes have been characterized, and some of which may contribute to the observed heterosis. For example, overexpression of wheat hybrid up-regulated gene (ADP-ribosylation factor, TaARF) in Arabidopsis displayed increased growth rates during the seedling and adult stages [16]. Overexpression of Larix hybrid up-regulated gene LaAP2L1, a member of the AP2/EREBP transcription factor family, led to markedly enlarged organs and heterosis-like traits in Arabidopsis [17]. Expression of an up-regulated protein ZmACT2 in dry embryos of maize hybrid in Arabidopsis partially complemented the low germination phenotype in the Atact7 mutant [18].

Heterosis affects nearly any trait in nearly every hybrid, hence one of the major challenges for expression analysis is deciding which tissue to be analyzed [19,20]. It was proposed that seedling leaves can be used as a model system to investigate the molecular basis of maize heterosis, because it is commonly observed that hybrids produce larger leaf areas than their corresponding parental lines [20–24]. At the cellular level, a crucial effect of leaf size heterosis is manifested by primarily increases in cell number, not cell size [25–27]. Recent study provided molecular evidence for the relationship between cell proliferation and heterotic maize growth. For example, the expression level of maize CNR gene, ortholog of fruit weight 2.2 (fw2.2) in tomato, was found to be negatively correlated with growth activity and...
hybrid vigor [28]. Collectively, it reveals that the study of cell number control is eminently important to understanding the underlying mechanism for leaf size heterosis.

In Arabidopsis, auxin signaling plays a vital role in leaf growth and development processes and some key genes, including AtARF2, AtARF7 and AtARF19, have been identified [29–31]. In our previous study, 31 maize genes that encode ARFs (Auxin Response Factors) were identified in maize genome, and phylogenetic analysis demonstrated that two of them, ZmARF10 and ZmARF25, were homologous to Arabidopsis growth repressor AtARF2 [32]. In this study, the expression patterns of ZmARF10 and ZmARF25 in different leaf regions of maize hybrids and their parental lines at the 5 DAG. B, C and D indicated as basal region, tip region and basal region, respectively. β-actin was used as an endogenous control. Data are represented as the mean ± SE (n = 3), * refers to significant at p<0.05, ** refers to significant at p<0.01. doi:10.1371/journal.pone.0094830.g001

Materials and Methods

Plant Materials and Growth Conditions

Maize inbred lines Mo17, B73, Zong3, 87-1 and their hybrids Mo17/B73, B73/Mo17, Zong3/87-1, 87-1/Zong3, B73/Zong3, Zong3/B73, B73/87-1 and 87-1/B73 were used for this study. Maize seeds were imbibed at 28°C in the dark, and the seeds after germination were selected with the same length of coleoptile (2.0 cm) to grow in hydroponic culture on a 16 h light/8 h dark cycle, at a temperature of 29°C and 25°C for the light and dark cycle, respectively. In maize leaf, the mature zone is composed of fully differentiated cells and cell division is restricted to the growing zone composed of immature cells [19,33]. Therefore, thirty millimeters from the base of the third leaves and twenty millimeters from the tip of the same leaf of a seedling 5 days after germination (DAG) were dissected and harvested for RNA extractions.
Arabidopsis (Col-0) seeds were sterilized by a 60 s 70% ethanol treatment followed by 1% NaClO within 10 min, four washes in distilled water, and chilled at 4°C for 3 days. Seeds were sown on half-strength Murashige and Skoog (MS) plates with 3% sucrose and 0.8% agar in a culture room at 22°C under a 16/8 light/dark cycle. After germination, 10-day-old Arabidopsis seedlings were transplanted and grown at a density of four plants per pot containing a mixture of soil and vermiculite (2:1) at 22°C under a 16/8 light/dark cycle with 70% relative humidity.

Leaf Area Measurements
Leaves were scanned using ImageScanner (GE Healthcare, USA), and measured with a public domain image analysis software (ImageJ version 1.32; http://rsb.info.nih.gov/ij/). For maize leaf area measurements, the third leaves were harvested in the morning (10:00–10:30 am) and experiments were done in three biological replicates and 10 plants of each genotype were analyzed for each replicate. The t-test was used to determine the significance of the differences in leaf areas between hybrid and the corresponding mid-parental value. The mid-parent heterosis (MPH) was calculated using the following formula: MPH = (F1 – mid-parental value)/mid-parental value in %, where F1 is the average value of hybrid, and the mid-parental value is the average value of the two parents.

Ten 30-day-old Arabidopsis plants of each transgenic line and wild-type were selected randomly for the fully expanded fifth leaf area measurements. The t-test was used to determine the significance of the differences in leaf area between transgenic plants and wild-type plants.

Histological Analysis
After the area measurements, the fully expanded fifth leaves of the ten 30-day-old Arabidopsis plants of each transgenic line and wild-type were used for epidermal cell size measurements. Leaves were first boiled in water for 10 min to kill the cells, and then immersed in 95% ethyl alcohol, after decolorized, they were transferred to hot (96°C) 85% lactic acid for 8 min. Finally, the leaves were transferred to room temperature lactic acid and examined using a Nikon Stereo Microscope. The number of epidermal cells was determined in an area of 0.58 mm² in the middle region of the fifth leaf blade. The average cell size was measured by dividing 0.58 mm² by the number of epidermal. The total number of cells per leaf was calculated by dividing the leaf area by the average cell size. Statistical calculations were performed with Microsoft EXCEL.

Isolation of DNA and Total RNA
Total DNA was extracted by the cetyltrimethylammonium bromide (CTAB) method [34] with minor modifications. Total RNA was extracted using a standard Trizol RNA isolation protocol (Invitrogen, USA), and then treated with RNase-free DNaseI (Promega, USA) to remove genomic DNA. The amount and quality of the total RNA were verified by electrophoresis on a 1% agarose gel. The concentration of RNA was measured using a NanoDrop spectrophotometer (ND-1000; NanoDrop Technologies). First-strand cDNA synthesis was performed using 2 µg of DNase digested total RNA with oligo(dT)15 primer according to the manufacturer’s protocol for RT-PCR first-strand synthesis (TaKaRa, Japan).
Quantitative RT-PCR Analysis
Quantitative RT-PCR (qRT-PCR) using SYBR Green PCR master mix (TaKaRa, Japan) was performed using CFX96 Real-Time PCR Detection System (Bio-Rad Laboratories, Inc., USA). Specific primers for qRT-PCR analysis were listed in Table S1. The PCR efficiency of all primer pairs was determined from standard curve experiments. PCR conditions consisted of an initial step at 94°C for 3 min followed by 35 cycles of 94°C for 25 s, 58°C for 25 s, and 72°C for 25 s; and then a final step at 72°C for 10 min. The PCR products were confirmed by visualization of the samples by electrophoresis on 1% agarose gel and stained by Ethidium bromide. The samples were extracted with MinElute Gel Extraction Kit (Qiagen, Germany), and these purified PCR products were cloned into pGEM-T plasmid vector (Promega, USA). Three clones were subsequently sequenced (Invitrogen, USA). The online tools, Open Reading Frame Finder (http://www.ncbi.nlm.nih.gov/orf/orf.html), Compute pI/Mw (http://web.expasy.org/compute_pi/), and InterPro (http://www.ebi.ac.uk/interpro/), were used to analyze the nucleotide and amino acid sequences.

Vector Construction and Plant Transformation
The coding region of ZmARF25 was introduced into pDONR221 vector using Gateway BP clonase enzyme mix (Invitrogen, USA) with the following primer pair: Gate-25-F and Gate-25-R (Table S1). To construct overexpression vector 35S::ZmARF25, the fragments were transferred from the pDONR221 vectors to pB2GW7 vector by Gateway LR recombination (Invitrogen, USA). This construct was transformed into Arabidopsis Col-0 via the floral dip method using Agrobacterium tumefaciens strain GV3101 [35]. Transgenic plants were selected on 1/2 MS medium containing herbicides (Basta). The herbicide resistant seedlings were transferred to a mixture of soil and vermiculite (2:1) and generated homozygous lines by self-fertilization. Statistical analysis of the difference in traits between transgenic plants and wild-type plants was performed by using t-test.

Results
Comparison of Maize Leaf Area between Hybrids and their Parental Lines
Previous studies revealed that maize hybrid exhibited heterosis in leaf size [24]. In this study, dynamic growth patterns of maize hybrid Mo17/B73 and its inbred parental lines were investigated in terms of the third leaf area and mid-parent heterosis (MPH) was calculated. The results exhibited that leaf areas of hybrid Mo17/B73 were significantly larger than its parental lines at 8, 10 and 12 DAG. Remarkably, MPH (72.00%) at 8 DAG was much higher than that of 10 and 12 DAG (60.50% and 58.26%) [Figure S1]. Thus, the third leaf areas of eight hybrids and their parental lines at 8 DAG were further measured and compared. It can be seen that the leaf areas of all hybrids were significantly larger than those of their parental lines at 8 DAG [Figure 1A].

Identification of a Hybrid Down-regulated Gene ZmARF25 in Maize Seedling Leaves
To gain insight into the relationship of ZmARF10 and ZmARF25 with leaf size heterosis, expression patterns of these two genes in the third leaves of hybrids Mo17/B73 and B73/Mo17 and their parental lines. Considering of the time lag between differential gene expression and the observed heterosis of leaf size at 8 DAG, the third leaves at 5 DAG were selected for qRT-PCR analysis. As shown in Figure 1B, the relative expression levels of ZmARF25 in the basal region of Mo17/B73 and B73/Mo17 hybrids were significantly lower than the levels observed in parental lines, whereas no significant differences in the expression patterns of ZmARF10 were observed in these hybrids. Most notably, no obvious expression alterations were detected for ZmARF10 and ZmARF25 in the leaf tip regions of the hybrids and their parental lines [Figure 1C]. Furthermore, the expression patterns of ZmARF25 between other hybrids and their parental lines were also investigated and we observed that ZmARF25 was down-regulated in all hybrid lines and its expression level was significantly lower than that of the parental lines.
regulated in the leaf basal regions of Zong3/87-1, 87-1/Zong3, B73/87-1, 87-1/B73 and Zong3/B73 [Figure 1D]. Therefore, \textit{ZmARF25} was selected for further investigation.

To obtain the cDNA with complete open reading frame (ORF) corresponding to \textit{ZmARF25}, cDNAs from B73 seedling leaves were amplified with \textit{ZmARF25}-F/R primer pair and one unique PCR fragment of about 2500 bp was produced (data not shown). The PCR products were cloned into \textit{pGEM-T} and three clones were sequenced. One 2552 bp fragment was obtained and no nucleotide polymorphisms were detected for all sequenced clones. Sequence analysis revealed that the PCR product contains a complete ORF, which encodes a polypeptide of 801 amino acids with a calculated molecular mass of 89.79 kD and isoelectric point of 6.09, which was consistent with our previous study [32].

Structure analysis exhibited that \textit{ZmARF25} has a typical ARF-type structure with a conserved DNA-binding domain (DBD) that consists of a plant-specific B3-type subdomain and an ARF subdomain required for efficient in vitro binding to the auxin response elements (AuxREs) in the N-terminus, a typical carboxy-terminal dimerization domain (CTD) with both III and IV subdomains and a middle region (MR) that might function as a repression domain (RD) since it is enriched in serine (S) [Figure 2] [36–39].

**Functional Analysis of \textit{ZmARF25} in Arabidopsis**

To investigate the possible function of \textit{ZmARF25}, overexpression \textit{Arabidopsis} transgenic plants were generated and herbicide-resistant \textit{T₀} transformants were transferred into soil and grown in a greenhouse to obtain segregating \textit{T₁} progeny for genetic analysis. Of the 21 transformants, eight overexpression lines showed a 3:1 segregation pattern for herbicide resistance, among which four (35S::\textit{ZmARF25} #1–4) were selected for further analysis. As shown in Figure 3A, the insertion of the overexpression vector was confirmed by genomic PCR. \textit{ZmARF25} is a homologue of \textit{AtARF2} in \textit{Arabidopsis} [32], the relative expression levels of exogenous gene \textit{ZmARF25} and endogenous gene \textit{AtARF2} in the transgenic and wild-type plants were analyzed by qRT-PCR. The results showed that different expression levels of \textit{ZmARF25} were observed in these overexpression lines, but the transcription of \textit{AtARF2} in the transgenic lines was not affected [Figure 3B]. Subsequent analysis was conducted using these \textit{T₃} homozygous transgenic plants. As shown in Figure 4, 35S::\textit{ZmARF25} #1–4 transgenic lines displayed markedly decreased leaf areas, shorter siliques and plant height with smaller inflorescences and flowers in comparison with wild-type. Further analysis revealed that the size of the fifth leaves of 35S::\textit{ZmARF25} plants was decreased by approximately 60–80% as compared to wild-type [Figure 4D]. In addition, the plant height and the silique length of transgenic plants were about 40–60% and 56% of that of wild-type, respectively [Figure 4E, F]. Collectively, these data indicated that overexpression of \textit{ZmARF25} in \textit{Arabidopsis} decreased the size of aerial organs by inhibiting organ growth and development.

To determine whether it is cell number or cell size, or both that contribute to the changed leaf size in transgenic lines, we observed...
and compared the size and number of cells in the fully expanded fifth leaves between 3SS:ZmARF25 and wild-type plants. The results showed that there was no distinct difference in cell size between the ZmARF25 overexpression and wild-type plants [Figure 5A, B], whereas cell number of 3SS:ZmARF25 plants was significantly lower when compared to wild-type plants [Figure 5C], indicating that the decrease in cell numbers, not cell size, was associated with the diminution of leaf size in 3SS:ZmARF25 plants.

Expression Analysis of Organ Size-associated Genes between 3SS:ZmARF25 Transgenic Lines and Wild-type

To elucidate the underlying regulation mechanism of ZmARF25, expression patterns of organ size-associated genes ActANT, AtGIF1, AtGRF5 and AtEXP10 between 3SS:ZmARF25 and wild-type plants were analyzed by qRT-PCR. The results showed that the expression levels of ActANT, AtGIF1 and AtGRF5 were significantly decreased in 3SS:ZmARF25 plants, whereas no obvious alteration of AtEXP10 expression was observed [Figure 6]. In Arabidopsis, AtGIF1, AtGIF2 and AtGRF5 were reported to be involved in cell proliferation while AtEXP10 played important roles in cellular expansion [40–44]. Collectively, it could be concluded that overexpression of ZmARF25 inhibited the transcription of cell proliferation associated genes, which is consistent with the decreased cell numbers observed in 3SS:ZmARF25 plants.

Discussion

ZmARF25 Repressed Organ Size by Decreasing Cell Numbers in Arabidopsis

Auxin response factors (ARFs) are transcription factors that bind with specificity to TGCTTC-containing AuxREs found in promoters of primary/early auxin response genes and mediate responses to the plant hormone auxin [36–39]. Genome-wide analysis revealed that ARF genes are represented by a large multigene family in plants [32,45–49]. Most ARFs contain a conserved N-terminal DBD, a variable MR and a typical CTD [36,37,45–49]. The DBD specifically binds to the conserved AuxRE, the CTD is modular with amino acid sequence related to domains III and IV in Aux/IAA proteins, making it function as a dimerization domain among the ARFs or with several Aux/IAA proteins. The structure of MR determines whether the ARF acts as an activator or repressor. Activation domain (AD) of ARFs is usually enriched in glutamine (Q), serine (S) and leucine (L), while repression domain (RD) is enriched in either S, L and proline (P); S, L and/or glycine (G) or S [32,39]. In this study, one hybrid down-regulated gene ZmARF25 that encoded a typical ARF-type protein was identified in maize. Most notably, ZmARF25 has a MR enriched in S, indicating that it might act as a repressor. Our previous study indicated that ZmARF25 was homologous to AtARF2 in Arabidopsis and OsARF4 in rice [32]. AtARF2 has been identified as a general repressor of cell division, one aspect of many biological processes regulated by auxin [29]. However, our knowledge about the functions and regulations of ZmARF25 gene is quite limited. Here, we demonstrated that overexpression of ZmARF25 in Arabidopsis resulted in significant size reduction of plant organs. Although the results of ZmARF25 overexpression in Arabidopsis may not fully reflect its precise functions in maize, it is reasonable to assume that ZmARF25 may be involved in maize growth and development process, which deserves for further investigation.

At the cellular level, organ size is determined by two developmental forces, cell proliferation and cell expansion, which partially overlap in time and are assumed to be coordinated [50]. Nevertheless, larger organ tends to be composed of more cells rather than bigger cells in different species [51]. In present study, we noted that overexpression of ZmARF25 in Arabidopsis significantly decreased the cell number, resulting in smaller organs in 3SS:ZmARF25 transgenic plants when compared to wild-type. Recently, some regulatory genes that affect leaf development have been identified and characterized at the molecular level. For example, loss of ActANT function reduces the size of all lateral shoot organs by decreasing cell number [41]. AtGIF and AtGRF5 act together and are required for the development of appropriate leaf size and shape by promoting and/or maintaining of cell proliferation activity in leaf primordial [42,43]. On the other hand, expansins are thought to function in the control of plant cell growth, and leaf size was substantially reduced in antisense lines with suppressed AtEXP10 expression, whereas overexpression of

Figure 5. Histological analysis of fully expanded fifth leaves of 3SS:ZmARF25 and wild-type plants. (A) Epidermal cells of the fully expanded fifth leaves of 3SS:ZmARF25 and wild-type plants. The statistics of (B) epidermal cells size and (C) cell number per leaf. Fully expanded fifth leaves of wild-type transgenic plants were analyzed. Data are represented as the mean ± SE (n = 10). t-test compared with the wild-type control: **refers to significant at p<0.01. doi:10.1371/journal.pone.0094830.g005

Figure 6. Expression patterns of organ size related genes in 3SS:ZmARF25 and wild-type plants. The aerial portions of 15-day-old seedlings were used for qRT-PCR analysis. ACTIN 2 was used as the endogenous control. Col represents the wild-type; #1–4 represents the four 3SS:ZmARF25 transgenic lines. Data are represented as the mean ± SE (n = 3). t-test compared with the wild-type control: *refers to significant at p<0.05, **refers to significant at p<0.01. doi:10.1371/journal.pone.0094830.g006
AtEXP10 resulted in plants with somewhat larger leaves [44]. Remarkably, overexpression of ZmARF25 repressed the expression levels of AtANT, AtARF5 and AtARF1, whereas no significant alteration in AtEXP10 expression was detected. Collectively, we speculate that ZmARF25 regulates the process of cell proliferation by altering the expression of AtANT, AtARF5 and AtARF1 in Arabidopsis.

Expression Patterns of ZmARF25 in Maize Hybrids and their Parental Lines Was Tissue and Genotype Dependent

Leaf differentiation proceeds basipetally (from tip to base) in a highly regular and continuous manner [52–54]. Maize leaves have a basal growing region, which is composed of immature cells, enclosed by older leaves [19,33,55]. Dynamics of the third leaf of maize seedling transcriptome and proteome along the maize leaf developmental gradient have been discussed. The results showed that genes and proteins expressed at the highest levels near the base of the leaf involved in cell wall biosynthesis, DNA synthesis, cell cycle regulation and chromatin structure regulation, protein metabolism, potential signaling proteins, auxin and brassinosteroid biosynthesis and signaling, respiratory pathways and vesicle transport [19,56]. Interestingly, relative expression level of ZmARF25 gene in the basal region of hybrids Mo17/B73 and B73/Mo17 was significantly lower than that of two parental lines. On the other hand, no significant alteration in expression was observed in the tip region, which is consistent with the observation that different regions within a leaf displayed different expression patterns [19,56]. Taken together, we proposed that leaf basal region was the appropriate tissue for further investigation of the molecular basis of leaf size heterosis.

Recently, many studies have analyzed heterosis-associated gene expression in leaves of maize, rice and wheat [7–14,20], but there has been no obvious consensus about genes that are differentially expressed in hybrids, which might be the result of significant differences in species, different genotypes within species, distinct tissues, experimental designs and statistical procedures applied [7–14,20]. In this study, we noted that the ZmARF25 gene was down-regulated in B73/Mo17, Mo17/B73, Zong3/87-1, 87-1/Zong3, B73/87-1, 87-1/B73 and Zong3/B73, but no significant expression difference was detected between B73/Zong3 and its parental lines, which may be attributed to the influence of maternal effect, because the mid-parent heterosis of hybrid B73/Zong3 was lower than that of Zong3/B73.

Down-regulation of ZmARF25 in Hybrids may Contribute to the Observed Heterosis for Leaf Size

Enlarged organ size, such as the increased leaf area, is an important feature of heterosis and also has a close relationship with the crop yield [12, 28 and 57]. A key observation made in maize heterosis was that the greater plant size is primarily (90%) due to increases in cell number, not cell size [25]. Recently study reported that transgenic over-expression of Zea mays ARGOS1 (ZAR1) enhanced maize organ growth [58]. The expression level of CNR gene was found to be negatively correlated with tissue growth activity and hybrid vigor [28,57]. In this study, the expression patterns of ZmARF10 and ZmARF25 in maize hybrids and their parental lines were analyzed. We found that ZmARF25 gene was down-regulated in hybrids. Moreover, 35S::ZmARF25 transgenic Arabidopsis plants displayed markedly decreased aerial organ size in comparison with wild-type. Considering the decreased cell number in 35S::ZmARF25 plant leaves, we proposed that the down-regulation of ZmARF25 gene in maize hybrid could accelerate cell proliferation and promote leaf development, which, in turn, contributes to the observed heterosis for leaf size.

Supporting Information

Figure S1 The third leaf area of hybrid Mo17/B73 and its parental lines at 8 DAG, 10 DAG and 12 DAG. H represents mid-parent heterosis (MPH). **refers to significant at p<0.01, data are represented as the mean ± SE (n = 3).

Table S1 Gene specific primer pairs used in this study.

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Author Contributions

Conceived and designed the experiments: ZFN QXS. Performed the experiments: CL CW LXM. Analyzed the data: CL JWX. Contributed reagents/materials/analysis tools: TYW HY YYY HRP ZRH. Wrote the paper: ZFN CL.

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