SIZ1-Mediated Sumoylation of ICE1 Controls CBF3/DREB1A Expression and Freezing Tolerance in Arabidopsis

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SIZ1 is a SUMO E3 ligase that facilitates conjugation of SUMO to protein substrates. siz1-2 and siz1-3 T-DNA insertion alleles that caused freezing and chilling sensivities were complemented genetically by expressing SIZ1, indicating that the SIZ1 is a controller of low temperature adaptation in plants. Cold-induced expression of CBF/DREB1, particularly of CBF3/DREB1A, and of the regulon genes was repressed by siz1. siz1 did not affect expression of ICE1, which encodes a MYC transcription factor that is a controller of CBF3/DREB1A. A K393R substitution in ICE1 [ICE1(K393R)] blocked SIZ1-mediated sumoylation in vitro and in protoplasts identifying the K393 residue as the principal site of SUMO conjugation. SIZ1-dependent sumoylation of ICE1 in protoplasts was moderately induced by cold. Sumoylation of recombinant ICE1 reduced polyubiquitination of the protein in vitro. ICE1(K393R) expression in wild-type plants repressed cold-induced CBF3/DREB1A expression and increased freezing sensitivity. Furthermore, expression of ICE1(K393R) induced transcript accumulation of MYB15, which encodes a MYB transcription factor that is a negative regulator of CBF/DREB1. SIZ1-dependent sumoylation of ICE1 may activate and/or stabilize the protein, facilitating expression of CBF3/DREB1A and repression of MYB15, leading to low temperature tolerance.

INTRODUCTION

Frosts cause substantial agricultural yield losses, particularly if a freezing event occurs during reproductive development. Low temperatures also substantially limit the geographic locations where crops can be grown (Guy, 1990). Temperate plants have evolved a capacity to survive freezing exposure through adaptive processes, many of which are initiated in response to low temperature exposure, a phenomenon referred to as cold acclimation (Guy et al., 1985; Thomashow, 1999). Research over the last decades has exploited the genetic variation for cold acclimation that exists in temperate flora and has provided comprehensive characterization of freezing stress injury and comparative physiological and biochemical dissection of low temperature hardiness processes (Guy et al., 1985; Thomashow, 1999). Recently, the molecular genetic tractability of Arabidopsis thaliana has led to a more insightful understanding of critical cold acclimation and tolerance processes (Thomashow, 1999). Cellular processes that contribute to cold acclimation include protection and stabilization of cellular membranes, enhancement of antioxidative mechanisms, and synthesis and accumulation of cryoprotectant solutes and unique cryoprotective proteins (Mahajan and Tuteja, 2005).

Low temperatures initiate signaling pathways that control the expression of genes encoding determinants that are necessary for chilling tolerance (Gong et al., 2002; Hsieh et al., 2002), cold acclimation, and freezing tolerance (Guy et al., 1985; Lang and Palva, 1992; Knight et al., 1999; Thomashow, 1999; Chinnusamy et al., 2006; Yamaguchi-Shinozaki and Shinozaki, 2006). Cold signaling is transduced through intermediate processes, such as inositol 1,4,5-triphosphate–mediated Ca2+ signatures, reactive oxygen species, abscisic acid (ABA), and mitogen-activated protein kinase signaling cascades, and RNA metabolism (Kovtun et al., 2000; Teige et al., 2004; Chinnusamy et al., 2006). Numerous transcription factors that facilitate cold signaling and control expression of genes in cold regulons have been identified (Shinozaki et al., 2003; Cook et al., 2004; Gilmour et al., 2004; Kaplan et al., 2004; Chinnusamy et al., 2006; Yamaguchi-Shinozaki and Shinozaki, 2006).

The most characterized transcription factors that regulate cold signaling include the C-Repeat (CRT)/dehydration responsive element (DRE) binding proteins CBF/DREB1 (Yamaguchi-Shinozaki and Shinozaki, 1994; Liu et al., 1998; Thomashow 1999). Three CBF/DREB1 proteins, CBF1/DREB1B, CBF2/DREB1C, and CBF3/DREB1A, transactivate cold-dependent and ABA-independent expression of COR/RD/LTI (for cold-responsive/responsive to dehydration/low-temperature-induced)
genes through the interaction between the AP2/ERF DNA binding domain of the transcription factor and core CRT/DRE cis-elements (A/GCCGAC) that are present in promoters of the target genes (Baker et al., 1994; Yamaguchi-Shinozaki and Shinozaki, 1994; Thomashow, 1999). Low temperatures transiently induce expression of all CBF/DREB1 transcription factors within minutes (Vogel et al., 2005). Overexpression of each CBF/DREB1 constitutively induces the CBF/DREB1 regulon and enhances plant freezing tolerance, indicating that these transcription factors are sufficient for cold acclimation (Gilmour et al., 2000, 2004). However, a loss-of-function cbf2 mutation causes freezing tolerance and cold hyperinduction of CBF1/DREB1B, CBF3/DREB1A, and CBF/DREB1 regulon expression, suggesting that CBF2/DREB1C negatively regulates CBF1/DREB1B and CBF3/DREB1A (Novillo et al., 2004). CBF3/DREB1A may negatively regulate CBF2/DREB1C (Chinnusamy et al., 2003, 2006).

Direct regulators of CBF/DREB1 expression are HOS1, ICE1, and MYB15 (Agarwal et al., 2006; Chinnusamy et al., 2006; Dong et al., 2006). The HOS1 (for high expression of osmotically responsive genes) RING-type ubiquitin E3 ligase negatively regulates cold-induced CBF/DREB1 expression (Ishitani et al., 1998). ICE1 (for inducer of CBF/DREB1 expression 1) is a MYC-like basic helix-loop-helix transcription factor that activates CBF/DREB1 expression in response to low temperatures (Chinnusamy et al., 2003). ICE1 binds to canonical MYC cis-elements (CANNNTG) in the CBF3/DREB1A promoter to induce expression, which then leads to induction of CBF/DREB1 regulon expression (Chinnusamy et al., 2003; Lee et al., 2005). ICE1 protein apparently is a focal controller of CBF3/DREB1A, CBF/DREB1 regulon gene expression, and cold tolerance responses (Chinnusamy et al., 2003). Recently, it was determined that HOS1 negatively regulates ICE1 function in low temperature adaptation (Dong et al., 2006). HOS1 migrates to the nucleus in response to cold treatment and polyubiquitinates ICE1, targeting this transcription factor for proteasome degradation (Lee et al., 2001; Dong et al., 2006). MYB15 binds to CBF/DREB1 promoter regions and represses expression of CBF/DREB1 and the CBF/DREB1 regulon and negatively regulates freezing tolerance (Agarwal et al., 2006). ICE1 also physically interacts with MYB15 and attenuates MYB15 expression (Agarwal et al., 2006). Together, these results indicate that the ubiquitin E3 ligase HOS1, MYC transcription factor ICE1, and MYB transcription factor MYB15 function in a regulatory cascade to modulate expression of CBF3/DREB1A, and perhaps other CBF/DREB1s, to control plant responses to low temperatures.

SUMO (for small ubiquitin-related modifier) conjugation to protein substrates (sumoylation) is a reversible posttranslational modification that is regulated by environmental stimuli in animals and yeasts (Johnson, 2004). Sumoylation/desumoylation of substrates affects critical and diverse processes, such as innate immunity, chromosome segregation and cell division, DNA repair, nucleocytoplasm trafficking, subnuclear targeting,

Figure 1. SIZ1 Mediates Freezing Tolerance.

(A) and (B) Nonacclimated (A) or cold-acclimated (B) wild-type (Col-0), siz1-2, and siz1-3 plants were exposed for 1 h to the temperature indicated, and photographs are of plants 7 d after freezing treatment.

(C) Freezing sensitivity of siz1-2 plants is suppressed by Pro35S:SIZ1:GFP expression. Photographs are of nonacclimated or acclimated plants 7 d after 1 h of incubation at –4 or –6°C, respectively.

(D) Electrolyte leakage from nonacclimated or acclimated (acclim) wild-type, siz1-2, and siz1-3 plants after exposure to the temperature indicated (programmed to cool at 2°C h⁻¹). Data are means ± SE (n = 4 leaves, each from a different plant).

(E) Electrolyte leakage difference between nonacclimated (white bars) or acclimated (gray bars) siz1 and wild-type plants (ELsiz1-ELwt) after exposure to the temperature indicated as in (D).
transcriptional regulation, and ubiquitin-mediated protein degradation by proteasomes (Gill, 2005; Hay, 2005). PIAS (for protein inhibitor of activated STAT)/Siz (for SAP and Miz) proteins are SUMO E3 ligases that mediate the final step of SUMO conjugation (Kahyo et al., 2001; Johnson and Gupta, 2001; Kotaja et al., 2002; Takahashi et al., 2003; Hay, 2005). Transcription factors are direct targets of SUMO conjugation that is mediated by PIAS/Siz proteins (Gill, 2005). SUMO conjugation affects transcription factor function through activation, repression, or protein stabilization processes. Yeast SUMO E3 ligases, Siz1 and 2, facilitate cell division at low temperatures (Johnson and Gupta, 2001). SUMO conjugation/deconjugation in plants has been implicated in responses to heat shock, oxidative stress, hypoxia, phosphate limitation, ABA, flowering, and pathogen defense (Kurepa et al., 2003; Lois et al., 2003; Murtas et al., 2003; Miura et al., 2005; Yoo et al., 2006; Lee et al., 2007). Recently, the Arabidopsis SUMO E3 ligase SIZ1 has been shown to participate in responses to phosphate starvation, salicylic acid–mediated signaling in plant defense, and basal thermotolerance (Miura et al., 2005; Yoo et al., 2006; Lee et al., 2007).

This study establishes that SIZ1 (Miura et al., 2005) is a regulator of cold acclimation by controlling ICE1 activity, CBF/DREB1 expression, particularly CBF3/DREB1A, and target gene function. A K393R mutation blocks sumoylation of ICE1, represses expression of CBF3/DREB1A and its regulon genes, and reduces freezing tolerance. We present evidence that sumoylation of ICE1 represses polyubiquitination of the protein that leads to enhanced stability of ICE1 at low temperatures. Sumoylation of ICE1 also represses expression of the negative regulator MYB15. Together, these results indicate that SIZ1-mediated SUMO conjugation/deconjugation of ICE1 is a key process that initiates many changes in gene expression that are required for low temperature tolerance.

RESULTS

SIZ1 Regulates Freezing and Chilling Tolerances

The siz1-2 and siz1-3 T-DNA insertion alleles, which impair SIZ1 SUMO E3 ligase function (Miura et al., 2005), caused freezing sensitivity based on survival (Figures 1A to 1C) and electrolyte leakage assays (Figure 1D). Electrolyte leakage from unacclimated siz1 plants was approximately twice that of the wild type at 0 to −3°C (Figure 1D) even though leakage was similar at 23°C (data not shown; Lee et al., 2007). siz1 plants were impaired in cold acclimation capacity compared with wild-type plants (Figure 1D), particularly at temperatures below −3°C (Figure 1E). The

![Figure 2. SIZ1 Is a Positive Regulator of CBF/DREB1 Expression, Particularly of CBF3/DREB1A.](image)

Relative mRNA levels in wild-type (white bars) and siz1-2 (black bars) seedlings were determined by quantitative RT-PCR analyses. Ten-day-old seedlings that were grown at 23°C were incubated at 0°C for the indicated time. Transcript abundances of SIZ1; CBF1/DREB1B, CBF2/DREB1C, and CBF3/DREB1A; CBF/DREB1 regulon genes COR15A, COR47, KIN1, and RD29A; SuSy (cold induced but independent of CBF/DREB1); and CBF/DREB1 regulators ICE1, HOS1, and MYB15 are illustrated. Data are means ± sd (n = 4).
siz1 plants also were chilling sensitive, which was evident by comparison with the wild type after prolonged exposure to 4°C (see Supplemental Figure 1 online). Leaf chlorosis and necrosis of siz1 plants were visible after 3 weeks of chilling, but chlorophyll content of the wild type did not decline even after 6 weeks of chilling (see Supplemental Figures 1B and 1C online). Expression of the wild-type allele Procam35S:SIZ1:GFP suppressed the freezing sensitivity of siz1-2 plants, further confirming that SIZ1 is required for low temperature tolerance (Figure 1C).

**SIZ1 Controls CBF/DREB1 and CBF/DREB1 Regulon Gene Expression**

In wild-type plants, low temperatures of 10°C or less induce CBF/DREB1 expression within 15 min, and transcript accumulation increases with lower temperatures (Jaglo-Ottosen et al., 1998; Chinnusamy et al., 2003). Cold (0°C)-induced CBF/DREB1 transcript accumulation in siz1-2 seedlings was less than in the wild type over a 24-h time frame (Figure 2, middle panels). The siz1 mutation affected expression of CBF3/DREB1A more than that of CBF1/DREB1B or CBF2/DREB1C (Figure 2, middle panels).

Transcript accumulation of the CBF/DREB1 regulon genes COR15A, COR47, and KIN1 began 6 to 12 h after exposure of plants to cold (Gilmour et al., 1998; Figure 2, right panels). Low-temperature-induced COR15A, COR47, and KIN1 transcript accumulation was less in siz1-2 than in wild-type seedlings (Figure 2, right panels). However, expression of RD29A, another CBF/DREB1 regulon gene, was similar in plants of both genotypes (Figure 2, middle panels). This gene may be regulated by other processes, as the hos9 mutation increases RD29A expression independent of CBF/DREB1 (Zhu et al., 2004). Sucrose synthase (SuSy), which is cold regulated through a CBF/DREB1-independent pathway (Gilmour et al., 2000), exhibited similar expression patterns in wild-type and siz1-2 seedlings (Figure 2, right panels). These data indicate that SIZ1 controls cold signaling through the regulation of CBF/DREB1 expression, although not all genes of the regulon are affected. Cold-induced CBF3/DREB1A, CBF1/DREB1C, COR47, and COR15A expression also was repressed in siz1-3 plants (data not shown).

A positive regulator, ICE1, and negative regulators, HOS1 and MYB15, of CBF/DREB1 expression and freezing responses have been identified (Lee et al., 2001; Chinnusamy et al., 2003; Agarwal et al., 2006). HOS1 and ICE1 transcript accumulation was not substantially affected by cold and was similar in wild-type and siz1-2 seedlings (Figure 2, left panels). HOS1 mRNA abundance transiently decreases immediately after cold exposure but is similar to precold levels after 3 h (Lee et al., 2001), which was the first treatment time point in this experiment (Figure 2, left panels). ICE1 transcript abundance was similar in wild-type and siz1 plants even with cold treatment (Lee et al., 2005; Figure 2, left panels). On the other hand, MYB15 mRNA abundance was moderately upregulated by cold in wild-type seedlings (Agarwal et al., 2006) but was induced substantially in siz1 seedlings (Figure 2, left panels). The timing of cold-responsive MYB15 expression in siz1 seedlings resembled that of COR and KIN1 transcript accumulation (i.e., occurred later during the low temperature incubation period relative to CBF/DREB1 expression). These results indicate that SIZ1 negatively regulates MYB15 expression but does not alter appreciably the transcript level of HOS1 or ICE1.

**SIZ1 Facilitates Cold-Induced Accumulation of SUMO Conjugates**

Anti-SUMO1 conjugation products were accumulated in wild-type seedlings within 1 h after exposure to 0°C but to a much lesser extent in siz1-2 seedlings, at comparable times during cold treatment (Figure 3). Anti-SUMO1 detects both SUMO1 and SUMO2 (Murtas et al., 2003), which are the most closely related by sequence comparison among the eight family members (Kurepa et al., 2003) and may be functionally redundant (Kurepa et al., 2003). These data indicate that cold induces SIZ1-mediated SUMO1/2 conjugation in planta that is due presumably to the E3 ligase activity of SIZ1 (Miura et al., 2005). Heat shock and other environmental stresses also cause an increase in SUMO1/2 conjugation products (Kurepa et al., 2003; Miura et al., 2005; Yoo et al., 2006), implicating that sumoylation/desumoylation of protein targets may be a posttranslational regulatory process in abiotic stress signaling of plants.

**SIZ1-Mediated Sumoylation of ICE1 Facilitates CBF3/DREB1A Expression**

The siz1 mutation did not affect ICE1 expression (Figure 2), which infers that SIZ1 is not a transcriptional regulator of ICE1 but could regulate activity by posttranslational modification. SUMOplot (http://www.abgent.com/tool/sumoplot) predicted that ICE1 contains one SUMO conjugation motif (KKXE; Minty et al., 2000) with K393 as the acceptor residue. SIZ1 was necessary for sumoylation of ICE1 in vitro (Figure 4A) but did not facilitate
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Figure 4. SIz1 Facilitates Sumoylation of ICE1.

(A) SIz1 mediates in vitro sumoylation of ICE1. Affinity-purified recombinant GST-T7-ICE1 or GST-T7-ICE1(K393R) was used as a substrate in an in vitro sumoylation assay; reaction mixture contained yeast GST-ScAos1 (E1), GST-ScUba2 (E2), ScUbC9 (E2), and His-ScSmnt3 (SUMO) and Arabidopsis GST-SIz1 (E3) recombinant proteins (Takahashi et al., 2003; Miura et al., 2005), without (−) or with (+) protein. ICE1(K393R) has an amino acid substitution of the residue that is predicted to be a SUMO conjugation residue in ICE1. Unconjugated and SUMO-conjugated ICE1 proteins were detected with anti-T7 (T7-ICE1). Arrowhead indicates sumoylation site in ICE1. Unconjugated and SUMO-conjugated ICE1 proteins were detected with anti-T7 (T7-ICE1). Arrowhead indicates sumoylation site in ICE1.

(B) SIz1 mediates SUMO1 conjugation to ICE1 in protoplasts. Wild-type or siz1-2 protoplasts were cotransformed to express T7-SUMO1 and HA:ICE1 or HA:ICE1(K393R). CdnAs were cotransformed into protoplasts isolated from wild-type or siz1-2 plants (Jin et al., 2001) to assess if SIz1 facilitates sumoylation in planta. SUMO1 conjugation to ICE1 was moderately induced by cold treatment in the wild type but was not evident in cold-treated siz1-2 protoplasts (Figure 4B). Also, the K-to-R mutation blocked in vivo sumoylation of ICE1 (Figure 4B). Together, these results indicate that SIz1 facilitates sumoylation of ICE1 at the K393.

Transient expression of ICE1 but not of ICE1(K393R) in wild-type protoplasts induced CBF3/DREB1A transcript abundance in response to cold (see Supplemental Figure 2 online). Conversely, ICE1(K393R) but not ICE1 expression moderately increased MYB15 mRNA abundance (see Supplemental Figure 2 online). These results and those illustrated in Figure 2 are consistent with the premise that cold-induced, SIz1-mediated sumoylation of K393 in ICE1 induces CBF3/DREB1A and represses MYB15 expression.

The GAL4 DNA binding system was used to evaluate the effect of K393R on ICE1 transcriptional activator function (Chinnusamy et al., 2003; Tiwari et al., 2003). The effector plasmid was constructed by fusing the cDNA encoding ICE1, ICE1(K393R), or ARF5M (positive control; Tiwari et al., 2003) to the DNA binding domain of the yeast GAL4 transcriptional activator (Figure 4C). Expression of this cassette is driven by the 35S promoter of Cauliflower mosaic virus (CaMV). The effector plasmid [ICE1, ICE1(K393R), or ARF5M], the ProcAl-Glu-glucuronidase (GUS) reporter plasmid (Tiwari et al., 2003), and the plasmid encoding Renilla luciferase driven by the 35S promoter for normalization (Chinnusamy et al., 2003) were cotransformed into Arabidopsis protoplasts (Jin et al., 2001). Transient expression of ICE1 increased GUS reporter activity ~20-fold (Figure 4D) as reported (Chinnusamy et al., 2003). Expression of ICE1(K393R) activated GAL4-responsive transcription to an equivalent level of ICE1 in protoplasts, crude extract from protoplasts was separated by SDS-PAGE, and ICE1 was detected by protein gel blot analysis with anti-HA (WB: HA; bottom panel).

(C) Schematic representation of the effector and reporter plasmids used in the GAL4 transient expression assay (Chinnusamy et al., 2003; Tiwari et al., 2003). The ICE1 or ICE1(K393R) open reading frame was inserted into the effector plasmid. GAL4 DB is the DNA binding domain of the yeast transcription factor GAL4; GUS is the reporter gene; NOS is the terminator signal of the nopaline synthase gene; and Ps is the translational enhancer of Tobacco mosaic virus.

(D) Relative GUS activities after transfection with an effector vector (vector control), ICE1, ICE1(K393R), or ARF5M (positive control; Tiwari et al., 2003). Renilla luciferase activity was used for normalization; relative GUS expression [(GUSsample/LUCsample)/(GUSvector/LUCvector)] was calculated. Data are means ± se (n = 3).
Overexpression of ICE1 (ProCsV:ICE1) but not ICE1(K393R) [ProCsV:ICE1(K393R)] increased freezing tolerance of transformed wild-type plants (Figures 6A and 6B). Increased abundance of transgene transcripts was detected in plants of the different overexpression lines by RT-PCR (see Supplemental Figure 3 online). Freezing tolerance of ICE1-overexpressing plants obtained in this research (Figure 6A) was similar to that of ICE1-overexpressing plants reported in a prior publication (Chinnusamy et al., 2003; Figure 6A, ICE1oe). ICE1(K393R)-expressing plants were more sensitive to freezing stress than wild-type or vector control plants but less sensitive than siz1-2 plants (Figures 6A and 6B). Cold-induced transcript abundance of CBF3/DREB1A and the regulon genes COR15A and COR47 was greater in ICE1-overexpressing plants and less in ICE1(K393R) plants relative to the vector control wild type (Figure 6C). CBF3/DREB1B and CBF2/DREB1C expression was upregulated in ICE1-overexpressing plants, as reported (Chinnusamy et al., 2003), but was moderately down-regulated in ICE1(K393R) transgenic plants relative to plants transformed with the vector cassette. MYB15 was moderately upregulated by ICE1(K393R) overexpression (Figure 6C). These results indicate that sumoylation of ICE1 facilitates CBF3/DREB1A expression and freezing tolerance and that substitution of K393 to R represses CBF3/DREB1A and increases MYB15 expression.

**DISCUSSION**

Genetic and biochemical evidence indicates that the SUMO E3 ligase SIZ1 controls low temperature–dependent CBF/DREB1 regulon expression through the induction of CBF3/DREB1, most substantially CBF3/DREB1A, and facilitates chilling and freezing responses, including cold acclimation. The MYC-like transcription factor ICE1, which is necessary for low temperature induction of CBF/DREB1 (Chinnusamy et al., 2003), is a direct target of SIZ1-mediated SUMO1 conjugation. SIZ-mediated SUMO1 conjugation to K393 affects ICE1 activity to control CBF3/DREB1A expression (Figures 2 and 6C; see Supplemental Figure 2 online). MYB15 is a negative regulator of CBF/DREB1 expression presumably through an interaction with elements in the promoter regions, although there is no direct evidence of transrepressor function (Agarwal et al., 2006). Expression of MYB15 is upregulated in siz1 plants or by ICE1(K393R) expression (Figures 2 and 6C; see Supplemental Figure 2 online), indicating that unsumoylated ICE1 induces MYB15 expression. Thus, SIZ1-mediated SUMO1 conjugation to ICE1 facilitates induction of CBF3/DREB1A expression, repression of MYB15, and cold tolerance.

**SIZ1 Transduces Cold Signals and Mediates Low Temperature Tolerance**

SIZ1-mediated SUMO1 conjugation to ICE1 is induced by cold treatment (Figure 4B) and induces CBF3/DREB1A expression (Figure 6C; see Supplemental Figure 2 online). These results indicate that SIZ1-mediated sumoylation of ICE1 is an early event in low temperature responses of plants and induces signal cascades that regulate expression of genes that are necessary for cold tolerance. However, it is still not established how cold regulates SIZ1 E3 ligase function. SIZ1 expression is constitutive
and unaffected by cold, indicating that transcriptional regulation does not directly control SIZ1 function in low temperature tolerance. Transcriptome profiling analyses reveal that genes encoding SUMO, SUMO E1, SUMO E2, and SUMO proteases are not induced by low temperature stress (Lee et al., 2005), inferring that cold-induced sumoylation of ICE1 is not due to transcriptional regulation of the SUMO conjugation/deconjuga-
tion cycle. Identification of the regulators that control sumo-
ylation in any organism remains elusive. Thus, it remains unclear how this posttranslational control process transduces specific regulatory inputs (Hay, 2005).

It is plausible that low temperatures directly or indirectly induce posttranslational modification of SIZ1 that alters the regulatory function of the protein. The human PIASy is sumoylated at K35, which is necessary for PIASy E3 ligase activity that activates the transcription factor Tcf-4 (Ihara et al., 2005). Since Arabidopsis SIZ1 contains predicted sumoylation motifs, it is possible that SUMO conjugation regulates the function of the protein. TGF-β activates the p38 MAP kinase cascade that stabilizes the PIASxβ protein and enhances PIASxβ gene expression (Ohshima and Shimotohno, 2003). PIASxβ facilitates sumoylation of Smad4, which is necessary for transactivation function (Ohshima and Shimotohno, 2003).

Posttranscriptional control of SIZ1 function could be a result of subnuclear targeting. SIZ1 is located in nuclear speckles at 23°C (Miura et al., 2005), which is analogous to PIAS proteins that localize to mammalian promyelocytic leukemia (PML) nuclear bodies (Sachdev et al., 2001; Seeler and Dejean, 2003). The precise function of PML nuclear bodies is not clear, but these are implicated in both gene activation and repression because transcription factors and transcriptional coregulators, including chromatin-modifying proteins, colocalize to PML bodies (Ching et al., 2005). Cytochemical analyses and genetic evidence indicate that PML bodies interact with specific genes and are associated with transcriptionally active chromatin (Wang et al., 2004; Ching et al., 2005). Recently, subnuclear compartmentalization processes have been implicated in gene activation (Sharrocks, 2006). It is possible that low temperature affects subnuclear localization of SIZ1 and/or of ICE1 that alters CBF/DREB1 expression.

SIZ1-Mediated Sumoylation of ICE1 May Facilitate and Stabilize Transcription Factor Activity

ICE1 preferentially induces CBF3/DREB1A expression within minutes after exposure of plants to low temperatures (Baker et al., 1994; Chinnusamy et al., 2003; Gilmour et al., 2004). The paradigm is that cold stimulates ICE1 transcription factor activity, by some yet unknown processes, which facilitates CBF3/DREB1 expression.

Figure 6. ICE1 Sumoylation Facilitates Freezing Tolerance and Enhances CBF3/DREB1A and CBF/DREB1 Regulon Expression.

(A) Photographs are of representative plants 7 d after 1-h exposure to the indicated temperature. PCsV:ICE1 (line 8) or PCsV:ICE1(K393R) (line 8) was transformed into Col-0 plants. pCsV1300 transgenic lines were generated for use as a vector control. The ICE1 overexpressing line (ICE1oe) was used as a positive control (Chinnusamy et al., 2003).

(B) Survival was determined for 20 plants after freezing treatment at the indicated temperature. Data are means ± SE calculated from data of five independent experiments and three independent ICE1 (3, 8, and 12) and ICE1(K393R) (6, 7, and 8) expressing lines.

(C) Relative mRNA levels in plants of ICE1 (white bars) or ICE1(K393R) (black bars) overexpressing lines or a vector control line (hatched bars) were determined by quantitative PCR. Seedlings were either untreated (0 h) or treated with low temperature (0°C) for the indicated time. Data are means ± SD (n = 4).
SUMO Modification of ICE1 Represses MYB15 Expression

SUMOylation of ICE1 also negatively affects MYB15 transcript abundance, which presumably facilitates CBF3/DREB1A expression (Figure 6C; see Supplemental Figure 2 online). MYB15 represses CBF/DREB1, particularly CBF3/DREB1A expression (Agarwal et al., 2006). It is yet to be determined whether SUMO-conjugated ICE1 directly or indirectly represses MYB15. Sumoylation of the same transcription factor can result in induction or repression of different target genes (Gill, 2005; Hay, 2005). SUMO modification of p53 enhances transcription of p21, an inhibitor of cyclin-dependent kinase (Gostissa et al., 1999). Interestingly, sumoylation of p53 represses expression of the human ribosomal gene cluster gene that inhibits DNA replication (Schmidt and Müller, 2002). The overall effect of p53 sumoylation, however, is to mediate p53-dependent G1 cell cycle arrest (Müller et al., 2000; Megidish et al., 2002). Also, PIAS-mediated sumoylation of Smad4 causes activation or repression of specific genes (Ohshima and Shimotohno, 2003; Long et al., 2004a). Cold-induced MYB15 expression occurs much more rapidly and intensively in siz1 seedlings than in the wild type. Sumoylated ICE1 may negatively regulate MYB15, but ICE1(K393R) expression enhances MYB15 transcript abundance (Figure 6C; see Supplemental Figure 2 online).

CBF/DREB1 gene function is tightly regulated both transcriptionally and posttranscriptionally (Thomashow, 1999; Lee et al., 2001; Chinnusamy et al., 2006), presumably because uncontrolled CBF/DREB1 activation may be disadvantageous in particular environments. In fact, constitutive CBF/DREB1 overexpression results in dwarfism (Gilmour et al., 2004), and hyperexpression of CBF/DREB1 caused by a hos1 mutation results in freezing sensitivity (Ishitani et al., 1998). The results presented herein confirm that ICE1 is a key regulator of CBF/DREB1 expression and cold tolerance and that sumoylation is a critical process in determining ICE1 activity (Figure 7). SIZ1-mediated sumoylation may facilitate CBF/DREB1 expression, ICE1 stability, and MYB15 repression. SUMO1/2 conjugation to K393 of ICE1 is the apparent biochemical basis for these positive and negative control processes. Presumably, the relative affect of cold exposure on these positive and negative control processes can provide a fine-tuned balance of phenotypic responses that enable fitness to an environment that experiences different low temperature episodes.
Methods

Plant Freezing Assay

Wild-type (ecotype Col-0), szt1-2, and szt1-3 plants were grown for 3 weeks (from sowing) in soil at 23°C under a long-day photoperiod (16 h light/8 h dark). Plants grown under these conditions were considered nonacclimated. For cold acclimation, 3-week-old plants were incubated at 4°C for 7 d under a long-day photoperiod. Plant freezing tests were performed as described (Zhu et al., 2004). Briefly, plants were exposed to low temperatures in a controlled temperature chamber (model Tenney-JR; Tenney Engineering). For Figure 1, plants were exposed to 4 nonacclimated. For cold acclimation, 3-week-old plants were incubated light/8 h dark). Plants grown under these conditions were considered

Electrolyte Leakage from Leaves

Electrolyte leakage from fully developed rosette leaves of 3-week-old plants was assessed as described (Zhu et al., 2004), with modifications. Each leaf (5th or 6th rosette leaf) was placed into a tube containing 200 μL deionized water, an ice chip was added to initiate nucleation, and the tube was incubated in a refrigerated circular bath (NESLAB RTE-120). The temperature of the bath was programmed for a temperature decrease from 0 to −8°C by a continuous reduction of −1°C over 30 min until the desired temperature was reached. Each tube was removed from the refrigerated bath and then placed immediately into ice to facilitate gradual thawing. Deionized water (14 mL) was added to the sample that was then shaken overnight, after which the conductivity of the solution was determined with the Accumet model 20 pH/conductivity meter (Fisher Scientific). The tube was then incubated at 90°C for 1.5 h and cooled to room temperature, and conductivity of the solution was determined (i.e., 100% conductivity). Conductivities of four leaves, each from a different plant, were evaluated at the different temperature minima.

Quantitative RT-PCR

Total RNA was isolated using TRIzol reagents (Invitrogen) according to the manufacturer’s protocol. Three micrograms of RNA were used as template for first-strand cDNA synthesis using Superscript II reverse transcriptase (Invitrogen) and an oligo(dT)12-18 primer. Primer pairs for real-time PCR (see Supplemental Table 1 online) were designed as described (Miura et al., 2005). Real-time PCR amplification, validation experiments, and calculation of relative differences in expression level were performed as per instructions (User Bulletin 2 for ABI PRISM 7700 sequence detection system; Applied Biosystems) (Miura et al., 2005). Briefly, real-time PCR amplification was performed with 20 μL of reaction solution, containing 5 μL of 50-fold-diluted cDNA, 0.3 μM of each primer, and 1X Quantitect SYBR Green PCR Master Mix (Qiagen). Analysis was performed using the Applied Biosystems PRISM 7700 sequence detection system. Relative transcript abundance was calculated using the comparative Ct method (User Bulletin 2 for ABI PRISM 7700 sequence detection system). For a standard control, expression of Actin2 was used. After calculation of ΔCt (Ct, gene of interest − Ct, actin), ΔΔCt (ΔCt, test − ΔCt, wild type) was calculated as instructed. The relative expression level was calculated as 2−ΔΔCt. A ΔΔCt value for the wild type without cold treatment (0 h) was normalized to 1 [2−ΔΔCt, wild type 0 h − ΔΔCt, wild type 7 h = 20 = 1].

In Vivo Analysis of Sumoylation Profiles

Seeds were sown onto 1 Murashige and Skoog salts medium containing 3% sucrose (Miura et al., 2005). Ten-day-old seedlings were incubated at 0°C for the times indicated prior to harvesting. Total protein was extracted as described (Murtas et al., 2003, 2005). Total protein (200 μg) was separated by SDS-PAGE and then blotted. The gel blot was probed with anti-SUMO1 (kindly provided by G. Coupland; Murtas et al., 2003) and was detected using ECL plus (Amersham).

Purification of Recombinant Proteins and in Vitro SUMO Conjigation Assay

To introduce the T7 tag (MASMTGGQGQGM) into pGEX-5X-1 (Amersham), pET-21a (Novagen) and pGEX-5X-1 were digested with NdeI and EcoRI, respectively, and then incubated with T4 DNA polymerase for blunt-end ligation. The blunted vectors then were digested with XhoI. The DNA fragment containing the T7 sequence was separated on an agarose gel, collected using the QIAquick gel extraction kit (Qiagen) and ligated into the digested pGEX-5X-1. The resulting construct was named pGEX-S5-T7. The ICE7 open reading frame was amplified from cDNA (synthesized from RNA of 3-h cold-treated [0°C] seedlings) using pfu DNA polymerase (Stratagene), and the primers ICE1-77F and ICE1-HAR (see Supplemental Table 2 online). The PCR product and pGEX-S5-T7 were digested with EcoRI and XhoI and then ligated. The construct was designated as pGST-T7-ICE1. To make an ICE1(K393R) protein, AA11-G was replaced with AGG by site-directed mutagenesis using the primers ICE1K393R8 and ICE1K393R8 (see Supplemental Table 2 online) (Miura et al., 2005). The PCR product was cloned into pGEX-S5-T7. The resulting plasmid construct was named pGST-T7-ICE1(K393R). ICE1 recombinant protein constructs were transfected into Escherichia coli BL21(DE3). E. coli cells containing pGST-T7-ICE1 or pGST-T7-ICE1(K393R) were incubated at 37°C until cells reached mid-log phase of growth. Then, 0.1 mM isopropyl-β-D-galactoside was added, and cells were incubated at 18°C for 16 h. Crude extracts were purified using Glutathione Sepharose 4 Fast Flow (Amersham). Yeast proteins and Arabidopsis thaliana SIZ1 protein were purified as described (Takahashi et al., 2003; Miura et al., 2005). The in vitro sumoylation assay was performed as described (Takahashi et al., 2003; Miura et al., 2005). Briefly, 3 μg of GST-T7-ICE1 or GST-T7-ICE1(K393R) was added to a reaction mixture containing 1.8 μg GST-ScUbc2, 0.85 μg GST-ScAos1, 0.17 μg Scubc9, 3 μg His-ScSmt3, 2 μg GST-ScSIC1, 50 mM Tris-HCl, pH 7.4, 10 mM ATP, 2 mM DTT, and 5 mM MgCl2. The reaction mixture (30 μL) was incubated at 37°C for 1.5 h. Proteins were separated by SDS-PAGE, and immunoblot analysis performed with anti-T7 antibody (Bethyl Laboratories) was performed.

In Vitro Ubiquitination of ICE1

Arabidopsis MBP-HOS1 (cDNA clone was kindly provided by Jian-Kang Zhu; Dong et al., 2006) was purified using amylose resin (New England Biolabs) as instructed. Purified GST-T7-ICE1 was sumoylated in vitro as described above. ICE1 was purified using T7-Tag antibody agarose (Novagen). The ICE1 was washed three times and eluted according to the manufacturer’s instructions. ICE1 protein was added to the ubiquitination buffer containing 0.2 μg of human E1 and 0.4 μg of E2 Ubch5b (Boston Biochemicals), 1 μg of E3 (MBP-HOS1), 10 μg of bovine ubiquitin (Sigma-Aldrich), 1 mM MgCl2, 2 mM ATP, and 2 mM DTT. The mixture was incubated at 30°C for 4 h, and samples were separated by electrophoresis on 8% SDS gels.

Protoplast Purification and Immunoprecipitation Analysis

The ICE1 coding region was amplified with pfu DNA polymerase and the primers ICE1-HAF and ICE1-HAR (see Supplemental Table 2 online). The
Protoplasts were incubated for 36 h at 23°C. The plant was supported by grants from the Plant Diversity Research Center of the 21st Century Frontier Research Program of the Ministry of Science and Technology of the Republic of Korea (PFC0330401-00), the Environmental Biotechnology National Core Research Center Project of the Korea Science and Engineering Foundation (R1-2003-012-01002-00), and National Science Foundation Plant Genome Award DBI-98-13360. This work is Purdue University Agricultural Research Program Paper 2006-18044.

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