Plant Signaling & Behavior 8:12, e27342; December; © 2013 Landes Bioscience

# HOS1-mediated activation of *FLC* via chromatin remodeling under cold stress

Jae-Hoon Jung[1] and Chung-Mo Park[2,3,*]

[1]The Sainsbury Laboratory; University of Cambridge; Cambridge, UK; [2]Department of Chemistry; Seoul National University; Seoul, Korea; [3]Plant Genomics and Breeding Institute; Seoul National University; Seoul, Korea

**Keywords:** *Arabidopsis,* chromatin remodeling, cold stress, FLC, flowering time, FVE, HDA6, HOS1

The *Arabidopsis* E3 ubiquitin ligase HIGH EXPRESSION OF OSMOTICALLY RESPONSIVE GENE 1 (HOS1) has been shown to act as a negative regulator of cold responses by degrading the INDUCER OF CBF EXPRESSION 1 (ICE1) transcription factor through the ubiquitin/proteasome pathway. Notably, loss-of-function *hos1* mutants exhibit early flowering, and the transcript level of the floral repressor *FLOWERING LOCUS C* (*FLC*) is downregulated in the mutants. However, it is largely unknown how HOS1 regulates *FLC* transcription. We found that HOS1 activates *FLC* transcription by inhibiting the activity of histone deacetylase 6 (HDA6) under cold stress. Cold temperatures induce the binding of HOS1 to *FLC* chromatin in an FVE-dependent manner. Cold-activated HOS1 promotes the dissociation of HDA6 from *FLC* chromatin, and the cold effects disappear in both *hos1* and *fve* mutants. It is therefore clear that HOS1 regulates *FLC* transcription via chromatin remodeling, providing new insights into the signaling crosstalks between cold response and flowering time control.

Temperature is a major environmental factor that affects various aspects of plant growth and developmental processes. In particular, low temperatures severely limit global plant distribution and reproduction. Plants have evolved diverse cold acclimation mechanisms to sense temperature changes and increase tolerance to freezing temperatures.[1,2]

Floral transition is a distinctive developmental trait that is profoundly influenced during the process of cold acclimation. A floral repressor *FLOWERING LOCUS C* (*FLC*) plays an important role in the signaling crosstalks between cold response and flowering time control. It has been found that intermittent cold treatments delay flowering time by inducing *FLC* expression, and the cold effects on flowering time are diminished in *FLC*-deficient mutants.[3,4] However, it remain largely unknown how cold temperatures regulate *FLC* expression.

The E3 ubiquitin ligase HIGH EXPRESSION OF OSMOTICALLY RESPONSIVE GENE 1 (HOS1) has been proposed to be a cold signaling attenuator that negatively regulates cold-responsive genes, such as those encoding CBF (C-repeat-binding factor) and COR (COLD-REGULATED) transcription factors.[5-7] Under cold conditions, HOS1 functions as an E3 ubiquitin ligase to trigger the degradation of INDUCER OF CBF EXPRESSION 1 (ICE1) transcription factor, a direct upstream activator of *CBF3* gene.[7] Interestingly, cold temperatures do not influence the gene expression and protein abundance of HOS1 but promote its nuclear localization.[6]

It is notable that loss-of-function *hos1* mutants exhibit early flowering and the expression of *FLC* gene is suppressed in the mutants.[3,4] The previous studies have been focused on the role of HOS1 in cold acclimation, and molecular mechanisms underlying the HOS1-mediated regulation of *FLC* expression have not been explored. We have recently demonstrated that HOS1 upregulates *FLC* transcription by antagonizing the actions of FVE and its interacting partner histone deacetylase 6 (HDA6) under cold stress.[8] HOS1 physically interacts with FVE, and FVE is essential for the binding of HOS1 to *FLC* chromatin. HOS1 inhibits the binding of HDA6 to *FLC* chromatin in a FVE-dependent manner (**Fig. 1**). Interestingly, both FVE and HDA6 are not ubiquitinated by HOS1, suggesting that HOS1 modulates *FLC* transcription through mechanisms other than the ubiquitination-mediated degradation of target proteins. Our observations provide a noble role of HOS1 as a chromatin remodeling factor in regulating gene transcription in response to temperature changes.

It should be noted that the HOS1-FVE-HDA6 regulatory module is not the sole mechanism that underlies the early flowering phenotype of *hos1* mutants. It has been reported that HOS1 influences the abundance of CONSTANS (CO), a central activator of *FLOWERING LOCUS T* (*FT*), in the photoperiodic flowering pathway (**Fig. 1**).[9,10] HOS1 mediates CO ubiquitination to induce its degradation in response to phytochrome B-mediated red light signals as well as cold stress,[9,10] indicating that HOS1 plays a role in both light and temperature responses.

The previous and our own data demonstrate that HOS1, which is originally defined as an E3 ubiquitin ligase, is also involved in transcriptional control via chromatin remodeling, extending the repertoire of the roles of HOS1 in gene expression regulation.

*Correspondence to: Chung-Mo Park; Email: cmpark@snu.ac.kr
Submitted: 11/25/2013; Accepted: 11/26/2013; Published Online: 01/03/2014
Citation: Jung J, Park C. HOS1-mediated activation of *FLC* via chromatin remodeling under cold stress. Plant Signaling & Behavior 2013; 8:e27342; PMID: 24390058; http://dx.doi.org/10.4161/psb.27342

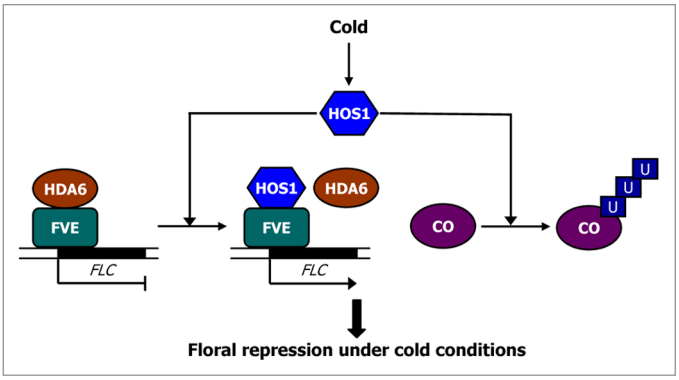


**Figure 1.** Dual roles of HOS1 in flowering time control under cold conditions. Under cold stress conditions, HOS1 binds to *FLC* chromatin via FVE and induces the dissociation of HDA6 from *FLC* chromatin, resulting in the activation of *FLC* transcription and delayed flowering. Moreover, HOS1 is involved in the control of CO abundance via an ubiquitination-mediated degradation pathway. HOS1 promotes CO degradation to inhibit the photoperiodic activation of *FT* under cold stress.

Given that HOS1 functions in various developmental processes, including hypocotyl elongation, primary root elongation, seed dormancy, flowering, and freezing tolerance, it is likely that HOS1 modulates the expression of a wide array of genes in plant genome via at least two distinct mechanisms: ubiquitin-mediated degradation and chromatin remodeling. In addition, it has been shown that the *hos1* mutants are insensitive to changes in ambient temperatures,[10,11] supporting the role of HOS1 in ambient temperature responses. It will be interesting to examine how changes in ambient temperature and cold stress responses are coordinated by HOS1.

### Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

### Acknowledgments

This work was supported by the Leaping Research (20120005600) and Global Research Lab (2012055546) Programs provided by the National Research Foundation of Korea, the Next-Generation BioGreen 21 Program (Plant Molecular Breeding Center No. 20120301305529001020O) provided by the Rural Development Administration, and by a grant from the Agricultural R and D Promotion Center (309017–05–4-HD140), Korea Ministry for Food, Agriculture, Forestry, and Fisheries. It was also supported in part by the Human Frontier Science Program (RGP0002/2012).

### References

1. Chinnusamy V, Zhu J, Zhu JK. Cold stress regulation of gene expression in plants. Trends Plant Sci 2007; 12:444-51; PMID:17855156; http://dx.doi.org/10.1016/j.tplants.2007.07.002
2. Zhu J, Dong CH, Zhu JK. Interplay between cold-responsive gene regulation, metabolism and RNA processing during plant cold acclimation. Curr Opin Plant Biol 2007; 10:290-5; PMID:17468037; http://dx.doi.org/10.1016/j.pbi.2007.04.010
3. Kim HJ, Hyun Y, Park JY, Park MJ, Park MK, Kim MD, Kim HJ, Lee MH, Moon J, Lee I, et al. A genetic link between cold responses and flowering time through FVE in *Arabidopsis thaliana*. Nat Genet 2004; 36:167-71; PMID:14745450; http://dx.doi.org/10.1038/ng1298
4. Seo E, Lee H, Jeon J, Park H, Kim J, Noh YS, Lee I. Crosstalk between cold response and flowering in *Arabidopsis* is mediated through the flowering-time gene *SOC1* and its upstream negative regulator *FLC*. Plant Cell 2009; 21:3185-97; PMID:19825833; http://dx.doi.org/10.1105/tpc.108.063883
5. Ishitani M, Xiong L, Lee H, Stevenson B, Zhu JK. *HOS1*, a genetic locus involved in cold-responsive gene expression in *Arabidopsis*. Plant Cell 1998; 10:1151-61; PMID:9668134
6. Lee H, Xiong L, Gong Z, Ishitani M, Stevenson B, Zhu JK. The *Arabidopsis HOS1* gene negatively regulates cold signal transduction and encodes a RING finger protein that displays cold-regulated nucleo—cytoplasmic partitioning. Genes Dev 2001; 15:912-24; PMID:11297514; http://dx.doi.org/10.1101/gad.866801
7. Dong CH, Agarwal M, Zhang Y, Xie Q, Zhu JK. The negative regulator of plant cold responses, HOS1, is a RING E3 ligase that mediates the ubiquitination and degradation of ICE1. Proc Natl Acad Sci U S A 2006; 103:8281-6; PMID:16702557; http://dx.doi.org/10.1073/pnas.0602874103
8. Jung JH, Park JH, Lee S, To TK, Kim JM, Seki M, Park CM. The cold signaling attenuator HIGH EXPRESSION OF OSMOTICALLY RESPONSIVE GENE 1 activates *FLOWERING LOCUS C* transcription via chromatin remodeling under short-term cold stress in *Arabidopsis*. Plant Cell 2013; 25:4378-90; PMID:24220632; http://dx.doi.org/10.1105/tpc.113.118364
9. Lazaro A, Valverde F, Piñeiro M, Jarillo JA. The *Arabidopsis* E3 ubiquitin ligase HOS1 negatively regulates CONSTANS abundance in the photoperiodic control of flowering. Plant Cell 2012; 24:982-99; PMID:22408073; http://dx.doi.org/10.1105/tpc.110.081885
10. Jung JH, Seo PJ, Park CM. The E3 ubiquitin ligase HOS1 regulates *Arabidopsis* flowering by mediating CONSTANS degradation under cold stress. J Biol Chem 2012; 287:43277-87; PMID:23135282; http://dx.doi.org/10.1074/jbc.M112.394338
11. Lee JH, Kim JJ, Kim SH, Cho HJ, Kim J, Ahn JH. The E3 ubiquitin ligase HOS1 regulates low ambient temperature-responsive flowering in *Arabidopsis thaliana*. Plant Cell Physiol 2012; 53:1802-14; PMID:22960247; http://dx.doi.org/10.1093/pcp/pcs123