SUMOylation is a process in which SUMO proteins are covalently attached to specific lysine residues in target proteins, thereby regulating various aspects of protein function, including transcription, subcellular localization, DNA repair, and cell cycle. Unlike the UPS, however, it does not directly degrade its target proteins. To date, 4 SUMO isoforms (SUMO1 to SUMO4) have been isolated in mammalian cells. Like ubiquitination, SUMOylation occurs through a series of enzymatic reactions. In the first step, SUMO precursors are converted to the active form of SUMO protein, exposing a glycine–glycine motif through cleavage of the carboxyl-terminal tails of the SUMO precursors via the hydrolase activity of sentrin-specific proteases. The glycine–glycine motif of the mature SUMO protein is covalently conjugated with a conserved catalytic cysteine in the heterodimeric SUMO-activating enzyme E1 via a thioester bond in an ATP-dependent reaction. Ubiquitin-conjugating enzyme 9 (UBC9), the only SUMO-conjugating E2 enzyme identified in mammalian cells, then attaches the SUMO protein directly to a lysine located within the consensus sequence Ψ-K-X-E/D (Ψ, hydrophobic amino acid; X, any amino acid) in the substrate. SUMO E3 ligases, such as the protein inhibitor of activated STAT (PIAS) family of proteins (PIAS1, PIAS3, PIASx, and PIASy), ring finger protein 4, Ran binding protein 2, and the polycomb protein 2, stimulate protein SUMOylation by associating with both UBC9 and substrates, thereby promoting poly-SUMO chain formation. Finally, SUMO proteins are removed from substrates by a family of isopeptidases called the SUMO-specific proteases, such as sentrin-specific proteases (Figure). Although SUMOylation is controlled primarily at the levels of E3 and SUMO proteases, the fact that UBC9 is the only E2 and that UBC9 is subjected to post-translational modifications, such as oxidation, nitrosylation, and SUMOylation, suggest the possibility that the function of UBC9 is regulated by stress and, in turn, it globally affects SUMOylation in cardiomyocytes in the heart.

Gupta et al. demonstrated that UBC9 conveys a compensation mechanism to eliminate PAO in the desmin-related cardiomyopathic heart. The molecular mechanisms by which UBC9 mediates degradation of PAO remain to be elucidated. Because elimination of PAO by UBC9 was attenuated in the presence of an inhibitor of the UPS, the protective effect of UBC9 is most
likely mediated through stimulation of the UPS. Perhaps the most straightforward hypothesis is that SUMOylation of the constituents of PAO, such as CryAB(R120G), induces degradation through recruitment of ring finger protein 4, an E3 ubiquitin ligase. However, in theory, the effect of UBC9 could be mediated through SUMOylation of any molecule involved in PQC, which in turn affects the activity of the UPS and the accumulation of PAO. For example, autophagy is a master regulator of PQC and eliminates misfolded proteins and damaged organelles. Growing lines of evidence point to an important role for SUMO in regulating autophagy. Beclin1 forms a complex with Vps34, thereby promoting both autophagosome formation and autophagosome–lysosome fusion. Formation of the Beclin1–Vps34 complex is tightly regulated by various post-translational modifications, such as phosphorylation.\(^5,8\) The Beclin1–Vps34 complex physically interacts with acetylated Hsp70, which in turn associates with SUMO E3 ligase KAP1. Vps34 is then SUMOylated at its Lys840, thereby stabilizing the interaction of Vps34 with Beclin1.\(^7\)

Recent evidence suggests that NEDDylation, another post-translational modification with ubiquitin-like protein NEDD8, also plays a critical role in PQC in cardiomyocytes...
by regulating both UPS and the autophagic pathway. Similar to SUMOylation, NEDDylation regulates a variety of biological processes, including DNA repair, cell cycle, signaling, nuclear transport, and transcription. NEDD8 is conjugated with the heterodimeric NEDD-activating enzyme E1 (APP-BP1/Uba3) via a thioester bond in an ATP-dependent reaction. Subsequently, ubiquitin-conjugating enzyme 12, the NEDD-conjugating E2 enzyme, attaches directly to the NEDD8. NEDD8 then interacts with culbin to form a complex with culbin-based RING ligases, a group of E3 ubiquitin ligases. The appropriate functioning of culbin-based RING ligases also requires deNEDDylation of culbin, catalyzed by the COP9 signalosome (CSN), a multiprotein complex consisting of 8 unique subunits (CSN1 through CSN8). Recently, the critical roles of CSN8/CSN in the cardiac PQC system have been revealed. Genetic ablation of the CSN8 gene resulted in impairment of both proteasomal function and autophagosome formation, which in turn caused cardiomyocyte necrosis and severe dilated cardiomyopathy. The results of the loss-of-function experiments suggest that SUMOylation and NEDDylation are not redundant. Although it is reasonable that important cellular functions, including UPS and autophagy, would be subjected to multiple layers of control, it would be worthwhile to investigate further the specific role of each mode of post-translational modification in controlling proteotoxicity in cardiomyocytes.

Dysregulation of SUMOylation contributes to several congenital and acquired heart diseases. SUMOylation-deficient mutations in lamin A, a protein responsible for maintaining nuclear structure and function, are associated with familial dilated cardiomyopathy and abnormalities in the cardiac conduction system. Cardiac transcription factors essential for development, including GATA4, TBXs, and Nkx2.5, are regulated by SUMOylation, and transduction of a non-SUMOylation mutant of Nkx2.5 in Nkx2.5−/− mice leads to congenital heart defects. SUMO1 is downregulated in failing hearts in humans and animals. Both SUMO1−/− and SUMO1−/− mice exhibit congenital heart defects with high mortality, whereas the phenotype of these mice is rescued by transduction of the SUMO1 gene. SUMOylation of SERCA2a on 2 lysine residues, Lys480 and Lys585, is required for stabilization and enhancement of the activity of SERCA2a, thereby positively regulating cardiac contractility. The level of SUMO-specific protease 1 (SEN1P1) was increased after ischemia/reperfusion, and the infant size after ischemia/reperfusion was greater in SEN1P1−/− than in wild-type mice. SUMOylation also modulates cardiac ion channel activity and mitochondrial dynamics. The activities of both Kv2.1 and Kv1.5, the voltage-gated potassium channels, are suppressed by SUMOylation. Mitochondrial fission is regulated by SENP5-mediated SUMOylation of Drp1, a GTPase that promotes scission of the mitochondrial outer membrane. A cautionary note here is that, because SUMOylation has such diverse functions in the heart in addition to its direct effects on PQC, modulation of SUMOylation may also affect PQC through many indirect mechanisms in vivo.

In summary, the study by Gupta et al suggests that UBC9 is a promising therapeutic target for the proteinopathies through modulation of SUMOylation-mediated protein degradation, as speculated by Gupta et al in the article. However, additional investigations are needed to advance UBC9 as a target for PQC enhancement. First, whether the beneficial effect of UBC9 is mediated primarily through enhancement of SUMOylation remains to be demonstrated. UBC9 has SUMOylation-independent effects, including direct stimulation of the unfolded protein response, another mechanism of PQC. The authors discussed the possibility that UBC9 may directly reduce protein misfolding by acting on protein folding. Because cardiac stress downregulates the level of free SUMO proteins, augmentation of UBC9 alone may not be able to restore the level of SUMOylation in cardiomyocytes with proteotoxicity. It would be interesting to test the effect of another intervention to stimulate SUMOylation, including upregulation of E3 ligases and SUMOs. Second, if SUMOylation is in fact able to facilitate PQC, identifying the direct target of SUMOylation that is responsible for the improvement of PQC would dramatically advance our understanding as to how the formation of PAOs is controlled. Identifying the specific E3 ligase and SUMO isoform responsible for the SUMOylation of the target may lead to the development of more specific interventions. Finally, it remains unknown whether changes in SUMOylation are involved in the pathogenesis of proteotoxicity in more common forms of heart disease and heart failure. It would, therefore, be helpful to conduct in vivo experiments in conjunction with the generation of gain- and loss-of-function mouse models of SUMOylation. Although it is generally accepted that both aging and oxidative stress facilitate proteotoxicity, the signaling mechanisms in the heart through which the production of misfolded proteins is increased and PQC is impaired are poorly understood. Identifying these endogenous mechanisms would provide us with valuable information that will be useful in combating heart failure.

Acknowledgments
We thank Daniela Zablocki for critical reading of the article.

Sources of Funding
This work was supported in part by US Public Health Service Grants HL67724, HL91469, HL102738, HL112330, and AG23039 (to J.S.). This work was also supported by the Fondation Leducq Transatlantic Networks of Excellence (to J.S.), ISPS KAKENHI Grant-in-Aid for Scientific Research (C) 26461126 (to Y.M.), and American Heart Association Scientist Development Grant 15SDG12070262 (to Y.M.).

Disclosures
None.

References
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SUMOylation Regulates Protein Quality Control


Key Words: cardiomyopathies ■ proteasome endopeptidase complex ■ small ubiquitin-related modifier proteins
SUMOylation: A Novel Protein Quality Control Modifier in the Heart
Yasuhiro Maejima and Junichi Sadoshima

Circ Res. 2014;115:686-689
doi: 10.1161/CIRCRESAHA.114.304989
Circulation Research is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 0009-7330. Online ISSN: 1524-4571

The online version of this article, along with updated information and services, is located on the World Wide Web at:
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