SCCRRO (DCUN1D1) Promotes Nuclear Translocation and Assembly of the Neddylation E3 Complex

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SCCRRO/DCUN1D1/DCN1 (squamous cell carcinoma-related oncogene/defective in cullin neddylation 1 domain containing 1/defective in cullin neddylation) serves as an accessory E3 in neddylation by binding to cullin and Ubc12 to allow efficient transfer of Nedd8. In this work we show that SCCRO has broader, pleiotropic effects that are essential for cullin neddylation by binding to cullin and Ubc12 to allow efficient transfer of Nedd8. In this work we show that SCCRO has a broader, pleiotropic effects that are essential for cullin neddylation in vivo. Reduced primary nuclear localization of Cul1 accompanying decreased neddylation and proliferation in SCCRO−/− mouse embryonic fibroblasts led us to investigate whether compartmentalization plays a regulatory role. Decreased nuclear localization, neddylation, and defective proliferation in SCCRO−/− mouse embryonic fibroblasts were rescued by transgenic expression of SCCRO. Expression of reciprocal SCCRO and Cul1-binding mutants confirmed the requirement for SCCRO in nuclear translocation and neddylation of cullins in vivo. Nuclear translocation of Cul1 by tagging with a nuclear localization sequence allowed neddylation independent of SCCRO, but at a lower level. We found that in the nucleus, SCCRO enhances recruitment of Ubc12 to Cul1 to promote neddylation. These findings suggest that SCCRO has an essential role in neddylation in vivo involving nuclear localization of neddylation components and recruitment and proper positioning of Ubc12.

The cullin family of proteins anchor Cullin RING finger-type E3 ubiquitination complexes (CRL) that regulate the degradation and activity of proteins involved in a wide range of cellular processes (1, 2). Several reports have shown that the activity of CRL complexes is primarily regulated by neddylation, a process mechanistically analogous to ubiquitination, where the cullin family of proteins are covalently modified by ubiquitin (Ub)-like protein Nedd8 (3–11). All cullin proteins in humans (Cul1, Cul2, Cul3, Cul4a, Cul4b, Cul5, and PARC) are subject to neddylation, with the exception of Cul7 (12, 13). Lethality resulting from knocking out core components in all organisms studied (except budding yeast) emphasizes the indispensable role of neddylation in normal cellular function (14–20).

Like ubiquitination, neddylation involves a sequential, tripartite enzymatic cascade (21, 22). The vertebrate enzymes for neddylation are the heterodimeric complex APP-BP1/Uba3 (E1) and Ubc12 or Ube2f (E2) (21, 23–25). The presence of enzymatic activity in the RING domain of Roc1 combined with its requirement and sufficiency to promote Nedd8 conjugation in vitro supports a role for Roc1 as the E3 for neddylation (26). Recent work identified a novel protein SCCRO/DCUN1D1/DCN1 (squamous cell carcinoma-related oncogene/defective in cullin neddylation 1, domain containing 1/defective in cullin neddylation) that binds to components of the E3 complex for neddylation (Ubc12 and Cul-Cul-Roc1) and increases neddylation efficiency in vitro (27–30). Biochemical studies and structural modeling suggest that DCN1 functions as an E3 promoting neddylation by reducing nonspecific Rub1 (Nedd8 in mammals) discharge and directing the active site of Ubc12 toward the acceptor lysine in Cdc53 (Cul1 in mammals) (31). These observations suggest that SCCRO is a nonessential component of the neddylation E3 complex that increases efficiency of the reaction. In contrast to in vitro observations, in vivo studies suggest that SCCRO has an essential role in neddylation, as knocking out SCCRO orthologs DCN1/Dcn1p in Caenorhabditis elegans and Saccharomyces cerevisiae results in reduced Cul3 neddylation and lethality (30). Our work shows that although SCCRO−/− mice are viable, neddylation is reduced, and these mice have several developmental defects including male specific infertility, runting, and high rates of perinatal mortality. In this work we show that in addition to assembling the neddylation E3 complex, SCCRO facilitates the subcellular localization of neddylation components, which is required for cullin neddylation in vivo. These findings help to explain the differential requirement for SCCRO in in vitro and in vivo models.

EXPERIMENTAL PROCEDURES

Plasmids—Human SCCRO and its mutants were cloned into pCMV-HA vector (Clontech) by standard PCR methodology

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EXPERIMENTAL PROCEDURES

Plasmids—Human SCCRO and its mutants were cloned into pCMV-HA vector (Clontech) by standard PCR methodology
buffer A, pH 7.9 (10 mM HEPES, 10 mM KCl, 0.1 mM EDTA, 0.1 mM EGTA, and 1 mM DTT) for 15 min on ice. Nonidet P-40 was added to 0.6%. After a quick vortex, nuclei were separated by centrifugation at 10,000 × g for 30 s. Nuclei were further lysed with an equal volume of radioimmune precipitation assay buffer.

**UV Irradiation**—MEFs were irradiated at 300 millijoules using GS Gene Linker (Bio-Rad). Cells were then incubated for another hour before harvest for immunoblotting or fixation for immunofluorescence.

**Antibodies and Immunoprecipitation**—The following antibodies were used in this study: anti-Cul1 (Zymed Laboratories), anti-Cul3 (BD Biosciences), anti-Roc1 (Abcam), anti-UB (P4D1) (Santa Cruz Biotechnology), anti-HA (Covance), anti-Myc (Santa Cruz Biotechnology), anti-FLAG (Sigma), anti-tubulin (Calbiochem), and anti-P300/CBP-associated factor (Santa Cruz Biotechnology). Anti-SCCRO monoclonal antibody was produced and utilized as described previously (27). Immunoprecipitations were performed essentially as described earlier (27). Immunoprecipitations were performed essentially as described earlier (27). Immunoprecipitations were performed essentially as described earlier (27).

**In Vivo and in Vitro Neddylation Assay**—For in vivo neddylation, cell lysates were directly subjected to immunoblotting for cullin(s). In vitro neddylation was performed essentially as described earlier (27). The source of Cul-Roc1 substrate was either endogenous or transfected cullins. The reaction mixture contained 2 μM recombinant Nedd8, 10 nM E1, and 4 mM ATP.

**Immunofluorescence**—Cy3-conjugated anti-HA, anti-Myc, and anti-FLAG and FITC-conjugated anti-HA antibodies were obtained from a commercial source (Jackson ImmunoResearch Laboratories). Cells transfected with plasmid(s) were seeded in 6-well plates with cover glass. Twenty four hours after transfection, cells were washed (PBS) and fixed in 4% formaldehyde for 10 min. The fixed cells were permeabilized with 0.5% Triton X-100 for 5 min, incubated in blocking buffer (PBS containing 10% FBS) for 30 min and stained overnight at 4 °C with fluorochrome-conjugated antibodies. The cells were washed three times with PBS, counterstained with 4',6-diamidino-2-phenylindole (DAPI), covered by ProLong Gold Antifade Reagent (Invitrogen), and examined with a Leica inverted confocal microscope fitted with appropriate fluorescence filters. For Cul1 staining, FITC-conjugated goat anti-rabbit secondary antibody was used. To calculate the percentage of cells with nuclear or nonnuclear localization, a minimum of 200 cells were counted for each experiment. All experiments have been repeated at least three times. Fisher’s exact test was used to compare results from localization studies, and a p < 0.05 was considered significant.

**Analysis of Mutant Mice**—Spleen, lymph nodes, and other organs were dissected free from littermates. Tissues were minced into dissociated cells in equal volume of media. The cell numbers were then counted, and cell sizes were determined by forward scatter analysis using flow cytometry.

**RESULTS**

**SCCRO Has Essential Function in Vivo**—Given the discrepancy in the function of SCCRO in vivo and in vitro, we first aimed to develop a model to define the requirement of SCCRO in vitro and assess mechanisms involved. Because body size changes can be attributed to either a decrease in cell size, cell number or both, running in SCCRO−/− mice provides an attractive model to investigate the in vivo requirement and functions of SCCRO (Fig. 1A) (35). We first confirmed that the smaller size of SCCRO−/− mice is independent of gender or genetic background.5 In addition, no obvious organ or hormonal defects that could explain the reduced body size were identifiably.5 We assessed cell size and number in several organs from littermate SCCRO−/− and SCCRO+/+ mice, showing no alteration in cell size in any organs tested (data not shown). Fewer cells were present in spleen and lymphatic tissues of SCCRO−/− mice, we focused on defects in proliferation. We isolated primary MEFs from day 12 SCCRO+/+, SCCRO−/−, and SCCRO+/+ littermate embryos. No detectable morphological differences were observed in MEFs of different genotypes. Forward scatter analysis using flow cytometry also revealed no significant differences in the size of these MEFs (Fig. 1B). However, a decrease in proliferation was seen in SCCRO−/− MEFs, confirming that the loss of SCCRO has physiological consequences (Fig. 1C).

In Vivo Functions of SCCRO Involve Its Neddylation Activity—To determine whether reduced proliferation of SCCRO−/− MEF is related to defective neddylation, we assessed levels of neddylated cullins. Despite similar levels of neddylated components (APP-BP1, Cul1, Ubc12, and Ned8) in SCCRO−/− and SCCRO+/+ MEFs, there was a decrease in the basal level of...
SCCRO-mediated Nuclear Transport Is Required for Cul1 Neddylation in Vivo—To define the cause for the differential requirement for SCCRO in vivo and in vitro, we elected to use U2OS, an established cell line that is more amenable to experimental manipulations than MEFs. For in vivo neddylation, U2OS cells were transfected with HA-Ubc12 and HA-SCCRO or HA-SCCRO-D241N and lysates subjected to immunoblotting for Cul1 or Cul3. For in vitro neddylation, reactions were activated by the addition of Nedd8, E1, and ATP to the lysates prior to immunoblotting. Consistent with prior findings, expression of Ubc12 alone was sufficient to promote cullin neddylation in vitro with co-expression of SCCRO enhancing the reaction (Fig. 3A, compare lanes 4 and 5 with 6). In contrast, whereas SCCRO promoted Cul1 and Cul3 neddylation in vivo, expression of Ubc12 alone had no effect (Fig. 3A, lanes 4 and 5). Co-expression of SCCRO with Ubc12 synergistically enhanced Cul1 neddylation (Fig. 3A, lane 6). Given that Ubc12 is primarily nuclear, these findings suggest that SCCRO-promoted nuclear translocation may be required for neddylation of cullins in vivo.

To assess the requirement of SCCRO-promoted nuclear translocation of Cul1 for neddylation, we developed a SCCRO construct with a canonical NES to block its nuclear translocation. Co-transfection of HA-Cul1 with HA-SCCRO or HA-NES-SCCRO in U2OS cells followed by immunoblotting for HA showed that SCCRO but not NES-SCCRO promotes Cul1 neddylation (Fig. 3B; compare lanes 2 and 3). Taken together, these findings suggest that SCCRO enhances cullin neddylation by promoting its nuclear translocation.

Binding Is Required for SCCRO-promoted Nuclear Translocation and Neddylation of Cul1—Structural modeling shows that the C-terminus of SCCRO binds to the Cul1 C-terminus in the terminal helix and the loop between the C-terminal two β strands (37). Consistent with this, we found that deletion or mutations in selected conserved residues within the C-terminus of Cul1 resulted in loss of binding based on immunoprecipitation assays (Fig. 4, A and B). To determine the requirement for binding to SCCRO for nuclear localization and neddylation, we expressed loss of binding mutants in U2OS neddylated Cul1 in SCCRO−/− MEF lysates as detected by immunoblotting (Fig. 2A, lanes 1 and 2, and supplemental Fig. 1). This difference was even more pronounced when neddylation was activated by supplementing the lysates with E1 (APP-BP1/Uba3), Nedd8, and ATP prior to immunoblotting (Fig. 2B). Moreover, global ubiquitination was also reduced in SCCRO−/− MEFS, suggesting that reduced cullin neddylation has functional consequences (Fig. 2B).

To determine whether the defect in cell proliferation is due to a loss of SCCRO-augmented neddylation, we expressed SCCRO in SCCRO−/− MEFS by retroviral infection and assessed effects on neddylation and proliferation. We expressed SCCRO-D241N, a mutant previously shown to lose neddylation promoting activity, as a control (27). Immunoblotting analysis showed that the levels of SCCRO in SCCRO−/− MEFS after retroviral infection were equal to that in SCCRO+/+ MEF (Fig. 2C). Expression of SCCRO but not SCCRO-D241N rescued both defective proliferation and Cul1 neddylation in SCCRO−/− MEF to wild-type levels (Figs. 1C and 2C). These findings suggest an association between the neddylation activity of SCCRO and its function in vivo.

SCCRO Promotes Nuclear Translocation and Neddylation of Cul1—The difference in requirement for SCCRO in vitro and in vivo may be explained by several factors, including post-translational modifications, compartmentalization, and/or requirement for other proteins/factors in the reaction. Work from Furukawa et al. (36) suggests that nuclear translocation may be required for cullin neddylation. Accordingly, we compared the subcellular distribution of Cul1 in SCCRO−/− and SCCRO+/+ MEFS. Interestingly, Cul1 was primarily nuclear in a significantly higher proportion of SCCRO+/+ (174/200; 87%) compared with SCCRO−/− (50/200; 25%) MEFS (Fig. 2D). Transgenic expression of SCCRO, but not SCCRO-D241N, in SCCRO−/− MEFS rescued the nuclear localization of Cul1 (Fig. 2D). To confirm that these observations are of physiological significance, we assessed cullin localization in response to neddylation-promoting stimuli. Among the various conditions tested, we found that UV irradiation resulted in the greatest increase in Cul1 neddylation and nuclear localization in SCCRO+/+ MEFS (Fig. 2, A and D). In contrast, no change in Cul1 neddylation or nuclear localization was observed in SCCRO−/− MEFS upon UV exposure (Fig. 2, A and D). Combined, these observations suggest that SCCRO plays an important role in nuclear translocation of Cul1, which may explain differences in its requirement for neddylation in vivo and in vitro.

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cells and assessed subcellular localization and neddylation of Cul1. We found that co-expression of SCCRO, but not SCCRO-D241N, increased the fraction of cells in which HA-Cul1 was primarily nuclear from ~72% to ~94% (Fig. 4D). Correspondingly, Cul1 mutants that lose SCCRO binding could not be neddylated or translocated to the nucleus even when co-expressed with SCCRO (Fig. 4, C–E).

Prior studies show that the Cul1-D610–615, which has reduced Roc1 binding, localizes to the cytoplasm, suggesting that binding to Roc1 may be involved in nuclear translocation. We confirmed that HA-Cul1-D610–615 does not bind to Roc1 and is primarily cytoplasmic when expressed in U2OS cells by immunoprecipitation and immunofluorescence analyses, respectively (Figs. 4D and 5A, lane 2). Co-expression of SCCRO
resulted in nuclear translocation of HA-Cul1-Δ610–615 (Fig. 4D). Validating a primary role for SCCRO in compartmentalization of cullins, the Cul1-Δ610–615/R764A double mutant, that loses both Roc1 and SCCRO binding, could not be translocated to the nucleus under any conditions tested (Fig. 4E).

Interestingly, defective neddylation of Cul1-Δ610–615 was also salvaged by co-expression of SCCRO but not SCCRO-D241N (Fig. 5B, lanes 2 and 3). In contrast, expression of NES-SCCRO was unable to promote nuclear translocation of Cul1-Δ610–615 (Fig. 5C). Because Roc1 is required for cullin...
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FIGURE 5. SCCRO rescues nuclear localization and neddylation of Cul1-Δ610–615. A, immunoblot on lysates from U2OS cells transfected with the indicated constructs and probed with anti-Myc or anti-HA antibodies following HA immunoprecipitation showing increased interaction between Roc1 and HA-Cul1-Δ610–615 with SCCRO co-expression (compare lanes 4 with 2 and 6). B, immunoblot on lysates from U2OS cells transfected with the indicated constructs probed with anti-HA antibodies showing rescue of HA-Cul1-Δ610–615 neddylation defect by SCCRO (top panel, lanes 2 and 6). C, immunofluorescence on U2OS cells co-transfected with FLAG-Cul1-Δ610–615 and HA-NESSCRO using Cy3-conjugated anti-FLAG antibody and FITC-conjugated HA antibody showing nuclear exclusion of SCCRO and loss of nuclear translocation of Cul1-Δ610–615.

neddylation, these findings suggest that SCCRO may help to recruit Roc1 to Cul1-Δ610–615 in the cytoplasm prior to nuclear translocation (36). To investigate this possibility, we performed immunoblot analysis after HA immunoprecipitation of lysates from U2OS cells co-transfected with Myc-Roc1 and HA-Cul1-Δ610–615 with Myc-SCCRO or Myc-SCCRO-D241N. Binding between Cul1-Δ610–615 and Roc1 was enriched with Myc-SCCRO co-expression but not Myc-SCCRO-D241N (Fig. 5A, lane 4). To validate these findings, we tagged Cul1-Δ610–615 with nuclear localization sequence (NLS-Cul1-Δ610–615) thereby targeting it to the nucleus independent of SCCRO. Co-expression of SCCRO could not rescue neddylation of NLS-Cul1-Δ610–615 (Fig. 6A, lane 4). These findings suggest that in addition to subcellular localization, SCCRO promotes neddylation by other mechanisms in vivo. Scott et al. showed that SCCRO restricts the otherwise flexible Roc1-Ubc12~Nedd8 and orients the Ubc12 active site toward the Cul1 acceptor Lys (31). This increases the efficiency of Nedd8 transfer to Cul1. However, its effect on neddylation of NLS-Cul1 in vivo appears more pronounced than that observed in in vitro reactions where molar excess of SCCRO is required to see any activity. Accordingly, in addition to proper positioning to facilitate Nedd8 transfer, we questioned whether SCCRO also promotes assembly of the neddylation E3 complex by enhancing recruitment of E2 in vivo. Immunoprecipitation of lysates for HA-Ubc12 showed an increase in Cul1 binding when SCCRO was co-expressed (Fig. 7B). We have shown previously that SCCRO preferentially binds to Ubc12~Nedd8 thioester, suggesting that recruitment of Ubc12 by SCCRO constitutes a functional complex. Combined, these observations suggest that in addition to Cul1 nuclear localization, SCCRO enhances ned-
A synergistic effect was seen with co-expression of both SCCRO and cullin after nuclear translocation. The rate-limiting step in Ub and Ub-like protein also share factors regulating reaction dynamics (38, 39). The rate-limiting step in Ub and Ub-like protein conjugation, respectively. Our laboratory, as well as others, have shown that neddylation of cullins can occur in vitro, but not wild-type Cul1, can be neddylated by the expression of Ubc12 alone. However, even after nuclear localization of Cul1 by tagging with NLS, co-expression of SCCRO with Ubc12 synergistically enhances neddylation, at levels much higher that that seen in vitro. These observations may be explained by enhanced recruitment of Ubc12 to Cul1-Roc1 by SCCRO in vivo.

Our findings raise several possibilities and questions. As the SCCRO-Cul1-Roc1 complex is relatively large, it requires active transport through a nuclear pore. However, none of the proteins in the complex contains a canonical nuclear targeting sequence. Although it is possible that a cryptic nuclear targeting sequence may be present, it is also possible that other unidentified proteins/factors may be involved in nuclear translocation. Second, given the conservation in reaction dynamics, these findings raise the possibility that CRL activity may also be regulated by compartmentalization. Interestingly, in our preliminary studies we found that neddylated cullins primarily exist in the nucleus, raising the possibility of ubiquitination occurring in the nucleus (supplemental Fig. 4). These findings need to be reconciled with reports suggesting SCCRO3 acts at the membrane to promote neddylation (44). Similar to work from Ma et al. (45), we found that SCCRO3 functions as a tumor suppressor in human cancers rather than an oncogene like other SCCRO family members. Our results suggest that SCCRO3 binds to Cul1 in vivo but has no independent neddylation activity, suggesting that its function may be context-dependent in vivo. Finally, as SCCRO4/DCUN1D4 and SCCRO5/DCUN1D5 both have a functional NLS in their N terminus, their role in neddylation remains to be explained.

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