Sumoylation is developmentally regulated and required for cell pairing during conjugation in Tetrahymena thermophila

Amjad M. Nasir  
_Purdue University_

Qianyi Yang  
_Purdue University_

Douglas L. Chalker  
_Washington University School of Medicine in St. Louis_

James D. Forney  
_Purdue University_

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The covalent attachment of small ubiquitin-like modifier (SUMO) to target proteins regulates numerous nuclear events in eukaryotes, including transcription, mitosis and meiosis, and DNA repair. Despite extensive interest in nuclear pathways within the field of ciliate molecular biology, there have been no investigations of the SUMO pathway in *Tetrahymena*. The developmental program of sexual reproduction of this organism includes cell pairing, micronuclear meiosis, and the formation of a new somatic macronucleus. We identified the *Tetrahymena thermophila* SMT3 (SUMO) and UBA2 (SUMO-activating enzyme) genes and demonstrated that the corresponding green fluorescent protein (GFP) tagged gene products are found predominantly in the somatic macronucleus during vegetative growth. Use of an anti-Smt3p antibody to perform immunoblot assays with whole-cell lysates during conjugation revealed a large increase in SUMOylation that peaked during formation of the new macronucleus. Immunofluorescence using the same antibody showed that the increase was localized primarily within the new macronucleus. SUMOylation is developmentally regulated and required for cell pairing during conjugation in *Tetrahymena thermophila*, including a dynamic regulation associated with the sexual life cycle.

The covalent attachment of small ubiquitin-like modifier (SUMO) to target proteins regulates numerous nuclear events in eukaryotes, including transcription, mitosis and meiosis, and DNA repair. Despite extensive interest in nuclear pathways within the field of ciliate molecular biology, there have been no investigations of the SUMO pathway in *Tetrahymena*. The developmental program of sexual reproduction of this organism includes cell pairing, micronuclear meiosis, and the formation of a new somatic macronucleus. We identified the *Tetrahymena thermophila* SMT3 (SUMO) and UBA2 (SUMO-activating enzyme) genes and demonstrated that the corresponding green fluorescent protein (GFP) tagged gene products are found predominantly in the somatic macronucleus during vegetative growth. Use of an anti-Smt3p antibody to perform immunoblot assays with whole-cell lysates during conjugation revealed a large increase in SUMOylation that peaked during formation of the new macronucleus. Immunofluorescence using the same antibody showed that the increase was localized primarily within the new macronucleus. To initiate functional analysis of the SUMO pathway, we created germ line knockout cell lines for both the SMT3 and UBA2 genes and found both are essential for cell viability. Conditional Smt3p and Uba2p cell lines were constructed by incorporation of the cadmium-inducible metallothionein promoter. Withdrawal of cadmium resulted in reduced cell growth and increased sensitivity to DNA-damaging agents. Interestingly, Smt3p and Uba2p conditional cell lines were unable to pair during sexual reproduction in the absence of cadmium, consistent with a function early in conjugation. Our studies are consistent with multiple roles for SUMOylation in *Tetrahymena*, including a dynamic regulation associated with the sexual life cycle.
Our previous studies in the ciliate *Paramecium tetraurelia* showed that RNA transcripts encoding SMT3 and UBA2 are up-regulated during macronuclear development, which occurs during sexual reproduction. RNA interference (RNAi)-induced silencing of these two genes during conjugation resulted in inhibition of programmed DNA rearrangements and failure to form a functional macronucleus (20).

In the current study, we report that modification of substrates by Smt3p is differentially regulated between vegetative and mating *Tetrahymena*. During conjugation SUMOylation increases, with the highest Smt3p adduct formation observed during the MAC differentiation stage. This is consistent with a role for SUMOylation in regulating the nuclear events of conjugation, specifically, the formation of a somatic MAC during conjugation in *Tetrahymena*. Vegetative cells depleted of Uba2p or Smt3p show increased sensitivity to DNA damage, as expected based on their roles in maintaining genome integrity. Interestingly, depletion of Uba2p or Smt3p prior to conjugation prevented pair formation, demonstrating a requirement prior to MAC development. These studies lay the foundation for an exceptional system to investigate the dynamics of SUMOylation.

### MATERIALS AND METHODS

**Strains and culture conditions.** Wild-type B2086 and CU428 strains of *Tetrahymena thermophila* were obtained from the *Tetrahymena* Stock Center, Cornell University, Ithaca, NY, USA. Strain B2086 contains 6-methylpurine-sensitive (MPR1) wild-type MACs that express mating type II. Strain CU428 contains 6-methylpurine-sensitive (MPR1) wild-type MACs that express mating type VII but contain micronuclei that have homozygous 6-methylpurine sensitivity (mpr1-1/mpr1-1). Cells were cultured in 1× SPP medium (2% proteose peptone, 0.1% yeast extract, 0.2% glucose, and 0.003% FeCl3) at 30°C. Cells in drops were examined at multiple times between 24 and 72 h after mixing.

**Construction of SMT3 and UBA2 germ line knockouts.** The targeting construct consisted of a neo3 cassette conferring paromomycin (pm) resistance placed under the control of the metallothionein (*MTTI*) promoter (21). The drug resistance gene was flanked by sequences upstream and downstream of the SMT3 coding sequence (the 5′ flank sequence was 1,141 bp [bp 187801 to 188942 of scaffold 8254555], and the 3′ flank sequence was 1,292 bp [bp 190002 to 191294 bp of scaffold 8254555]; GenBank accession number NW_002476326) or UBA2 coding sequence (5′ flank sequence was 1,004 bp [bp 477263 to 478327 of scaffold 8254719] and 3′ flank sequence was 1,148 bp [bp 476286 to 477434 of scaffold 8254719]; GenBank accession number NW_002476484) (see Table S1 in the supplemental material for a list of the primers). Wild-type B2086 and CU428 strains were mated, and the targeting construct was introduced 2.5 to 3.5 h postmixing, as described by Bruns and Cassidy-Hanley (22). Potential SMT3 and UBA2 micronuclear knockout (KO) strains were identified by selection with paromomycin (confirming insertion of the neo3 cassette) and 6-methylpurine (confirming successful conjugation and formation of new macronuclei). The heterozygous micro KO strains were further analyzed by PCR and genetic crosses to test strains (e.g., CU427) to confirm germ line segregation of paromomycin resistance. These heterozygous germ line transformatants were crossed with “star” strains B*VI* and B*VII*, which are deficient in donating a functional micronucleus. The subsequent uniparental transfer that occurs resulted in the generation of homzygous germ line knockout heterokaryon strains (23). The micronuclei (germ line) in these cells have homozygous deletions of the targeted gene, but the MAC genome is wild type because the two partners of “star” crosses do not proceed through conjugation to form new MACs. PCR analysis as well as genetic crosses confirmed the genotype of each KO heterokaryon (see Table 1 and Fig. 4, below).

**Viability test.** To test the viability of the progeny of SMT3 or UBA2 homozygous heterokaryons strains, starved SMT3 or UBA2 KO heterokaryons strains (−2×10^5^ cells/ml) were mixed to initiate mating, and mating efficiency was assessed at 2 h. Mating pairs were then isolated at 8 to 10 h postmixing in drops containing 1× SPP medium and placed at 30°C. Cells in drops were examined at multiple times between 24 and 72 h postmixing. The number of cell divisions that occurred before death of homozygous SMT3 and UBA2 KO progeny was calculated by counting the total number of cells at the time of death, dividing by two (two exconjugants per pair), and calculating the number of cell divisions based on exponential growth. To determine whether cells successfully completed conjugation in SMT3 or UBA2 heterokaryon KO crosses, cells were cultured in 1× SPP containing 80 μg/ml paromomycin. Progeny of the control cell lines wild-type B2086Δ2 X CU428Δ1 were tested for 6-methylpurine (7.4 μg/ml) resistance. Additional matings between SMT3 and UBA2 heterokaryons to wild-type partners were also performed to ensure generation of viable progeny (Table 1). To check for progression through conjugation, cells were fixed and stained with the DNA-specific dye diaminofluorescein diacetate (DAPI), as described below (see “Fluorescent and confocal microscopy”).

**Creation of GFP-SMT3 and GFP-UBA2 constructs.** To examine Smt3p and Uba2p localization in *Tetrahymena*, coding regions for Smt3p and Uba2p were amplified and cloned into the pENTR/D-TOPO plasmid (Invitrogen, Grand Island, NY), which is used for recombination with the Gateway cloning system, to create pENTR-SMT3 and pENTR-UBA2, respectively. LR Clonase II (Invitrogen, Grand Island, NY) was used for directional cloning of SMT3 or UBA2 into the destination vector pBSmtGFPneo3, which contained an N-terminal MTTI-inducible green fluorescent protein (GFP) expression cassette cloned upstream of a cycloheximide-resistant *Tetrahymena* pC50 locus (described in reference 24). For biostatic transformation, constructs were digested with HindIII or BglII to

### TABLE 1 SMT3 and UBA2 are essential genes

<table>
<thead>
<tr>
<th>Types of mating cells</th>
<th>No. individual pairs examined</th>
<th>No. wells with more than 2 cells/drop</th>
<th>No. of clones completed conjugation</th>
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</thead>
<tbody>
<tr>
<td>SMT3-neo3-1 X SMT3-neo3-2</td>
<td>110</td>
<td>34</td>
<td>0</td>
</tr>
<tr>
<td>UBA2-neo3-1 X UBA2-neo3-2</td>
<td>124</td>
<td>32</td>
<td>0</td>
</tr>
<tr>
<td>SMT3-neo3-1 X B2086</td>
<td>110</td>
<td>91</td>
<td>81</td>
</tr>
<tr>
<td>UBA2-neo3-1 X B2086</td>
<td>110</td>
<td>96</td>
<td>88</td>
</tr>
<tr>
<td>SMT3-neo3-2 X CU428</td>
<td>110</td>
<td>89</td>
<td>84</td>
</tr>
<tr>
<td>UBA2-neo3-2 X CU428</td>
<td>110</td>
<td>92</td>
<td>83</td>
</tr>
<tr>
<td>B2086 X CU428</td>
<td>88</td>
<td>82</td>
<td>82</td>
</tr>
</tbody>
</table>

* Each row represents data obtained in the course of three independent experiments.

To distinguish between cells that completed conjugation (progeny cells) and cells that had aborted conjugation, wild-type B2086 and CU428 strains were tested for resistance with 6-methylpurine (to which only progeny cells should be resistant), and cells from the ∆SMT3-neo3 X ∆SMT3-neo3 and ∆UBA2-neo3 X ∆UBA2-neo3 matings were checked for paromomycin resistance (progeny should be paromomycin resistant).
produce linear plasmid with flanking rpl29 sequences and transformed into starved Tetrahymena cells. Transformed cells were selected in SPP nutrient medium containing 12.5 g/ml cycloheximide. To induce GFP-SMT3 or GFP-UBA2 expression, 0.1 g/ml CdCl2 was added to vegetative and mitotic cells. For mating cells, 0.05 g/ml CdCl2 was added when cells were first mixed and then again at 6 h postmixing. Cells were fixed as described below (see “Fluorescent and confocal microscopy”).

**Fluorescent and confocal microscopy.** GFP-SMT3- or GFP-UBA2-expressing cells were fixed with 4% paraformaldehyde for 30 min at room temperature, washed with Tris-buffered saline (TBS) for 10 min, and stained with DAPI at 1 g/ml for 10 min. DAPI-stained cells were then placed on microscope slides, and 5 µl of VectaShield fluorescence mounting medium was applied to the cells. Fluorescence microscopy of vegetative strains expressing GFP transgenes (Fig. 1) was performed using a Zeiss LSM 710 confocal microscope. Digital images were processed using Zen 2009 (Carl Zeiss, Thornwood, NY) and Adobe Photoshop (Adobe Systems, Inc., San Jose, CA). Fluorescence images of mated cells (see Fig. 3, below) were obtained with an Olympus BX51TF model microscope with a 40X objective oil lens (UIS2/BPF1; Olympus).

**Generation of conditional mutants of SMT3 and UBA2.** UBA2 knockout heterokaryons of different mating types were mixed with each other to initiate mating. Cells undergoing MAC development (corresponding to 8 h postmixing) were biolistically transformed using the MTT1 promoter-expressed GFP-UBA2 transgene inserted at the rpl29 locus (cycloheximide resistance). Progeny that were successfully transformed (paromomycin resistant and cycloheximide resistant) were complete gene knockouts for wild-type UBA2 and expressed only the GFP-UBA2 form. SMT3 heterokaryons that were mated died in the first 24 h after conjugation, and we were unable to rescue cells using GFP-SMT3 as described above. To generate a conditional mutant of SMT3, CU522 and CU527 strains, which are sensitive to the drug paclitaxel (originally named taxol), were transformed with an MTTp-driven FLAG-His6-SMT3 construct (gift of Joshua Smith, Missouri State University), which was incorporated at the BTU1 locus, resulting in progeny that were paclitaxel resistant (method originally described in reference 25). FLAG-His6-SMT3-expressing strains were further transformed with the neo3 construct used earlier to generate SMT3 KO heterokaryons. Cells were cultured in increasing concentrations of paclitaxel and paromomycin to sort for FLAG-His6-SMT3 copies and the reduction of wild-type SMT3. Complete assortment of the wild-type SMT3 gene away from the FLAG-His6-SMT3 copy was demonstrated by performing two-step reverse transcriptase PCR (RT-PCR) on RNA obtained from FLAG-His6-SMT3-expressing strains which showed amplification of the FLAG-His6-SMT3 product only.
Mating *Tetrahymena* and assessment of pair formation. For conjugation, *T. thermophila* strains were cultured at 30°C in 1 × SPP to logarithmic phase and harvested at an optical density of 540 nm (OD$_{540}$) of 0.3, corresponding to 2 × 10$^5$ cells/ml. Cells were then washed with starvation buffer (10 mM Tris, pH 7.5) and then subsequently starved (16 to 24 h at 30°C) in 10 mM Tris (pH 7.5). Equal numbers of cells were then mixed together to initiate mating. To assess pair formation, conditional mutants of SMT3 or UBA2 were cultured under three different conditions. The +Cd cultures were grown in SPP medium supplemented with 0.1 μg/ml CdCl$_2$, for 24 h at 30°C. These cells were then starved in starvation buffer containing 0.1 μg/ml CdCl$_2$, for 24 h at 30°C, after which they were mixed to initiate mating pair formation. The −Cd cultures were grown and starved in the absence of CdCl$_2$, and then mated to assess pair formation. The +Cd addition cultures were treated as described for the −Cd set except that at 2 h prior to mixing, cells were supplemented with 0.1 μg/ml CdCl$_2$, and then mated. The percentage of cells forming pairs was calculated as the number of cells in pairs divided by the total number of cells in the sample (paired plus single cells).

Preparation of whole-cell extracts. Cultures (100 ml) of vegetative wild-type strains B2086.2 and CU428.1 at log phase (2 × 10$^5$ cells/ml) and wild-type mated cell cultures (at 0, 2, 5, 7, 10, 24, and 30 h postmixing) were harvested by centrifugation and washed twice with 10 mM Tris-Cl (pH 7.5). The cell pellet was resuspended in 2 ml of lysis buffer (8 M urea, 100 mM dithiothreitol, and 0.05% bromophenol blue). Samples were sonicated. The resulting lysate was centrifuged at 4°C for 30 min at 77,000 × g in an SW41 rotor (Beckman Coulter). The clarified supernatant was then prepared for Western blotting as described below.

Western blotting and Coomassie staining analyses. Clarified lysates from wild-type strains were prepared by the addition of SDS loading buffer to a final concentration of 1 × (50 mM Tris [pH 6.8], 10% glycerol, 2% SDS, 100 mM dithiothreitol, and 0.05% bromophenol blue). Samples were separated on 8% Bis-Tris gels by using Tris-glycine-SDS running buffer containing 0.1% SDS, 100 mM dithiothreitol, and 0.05% bromophenol blue). Samples were separated by electrophoresis on a gel and subsequently stained with Coomassie brilliant blue R-250 for 30 min at room temperature.

**RESULTS**

*Tetrahymena* Smt3p and Uba2p primarily accumulate in the macronucleus. Previous studies on *Paramecium tetraurelia* revealed that RNAi-induced silencing of UBA2 or SUMO resulted in the failure of programmed DNA rearrangements (20), but the underlying mechanism responsible for this effect was not established. *Tetrahymena* was selected for additional studies because of its technical advantages (gene knockouts, higher mating efficiency) and the opportunity for comparative analysis with *Paramecium*. To initiate our analysis of SUMOylation, we searched the Tetrahymena thermophila genome for homologs and identified a single gene encoding SUMO (26) with reciprocal top BLAST hits to SUMO proteins in *S. cerevisiae*, *Drosophila melanogaster*, and humans. We named the Tetrahymena gene SMT3 (TThERM_00410130) (20), consistent with *S. cerevisiae* nomenclature (suppressor of Mif two 3). The alignment of *Tetrahymena* Smt3p with human SUMO isoforms, *S. cerevisiae*, *Schizosaccharomyces pombe*, and other protozoa is shown in Fig. 1A. *Tetrahymena* Smt3p shares 50% identity with *S. cerevisiae*. The N-terminal regions show substantial divergence, but most of the protein is highly conserved, including the diglycine motif found on the mature C terminus of ubiquitin-like proteins (Ubls). A *Tetrahymena* homolog for UBA2 was previously reported based on its identity with *Paramecium tetraurelia* (TThERM_00391590) (20). That study evaluated the developmental expression of transcripts from the *Tetrahymena UBA2* and SMT3 (SUMO) genes with Northern hybridizations. Both showed substantial increases in expression during sexual reproduction, consistent with subsequent data from whole-genome microarrays (27). The developmental pattern of expression and sequence identity between these genes compared with the previously examined *Paramecium UBA2* and SUMO genes led us to perform additional studies.

To evaluate whether the cellular location of *Tetrahymena SUMOylation* pathway proteins is consistent with that in *Paramecium*, the cellular localization of Smt3p and Uba2p was examined by expressing GFP-SMT3 or GFP-UBA2 transgenes from a metallothionein promoter regulated by cadmium. Both Smt3p and Uba2p were observed in the somatic macronucleus and in the macronuclear mass. The signal at the macronuclear mass was detected with secondary antibody alone (no primary antibody) and is therefore unlikely to be significant. Additional experiments with the GFP transgenes showed that increasing or decreasing cadmium concentrations changed the strength of the GFP signal but did not alter its nuclear localization (data not shown). Although a small fraction of Uba2p and Smt3p is likely present in the cytoplasm, we are confident that the signal is predominantly macronuclear in vegetative cells. Studies of other developmental model systems, such as mice (28, 29), *Drosophila* (30, 31), and yeast (32), have reported that both Smt3p and Uba2p localize predominantly to the nucleus. This is expected, as many of the proteins modified by SUMO are nuclear, including promoter-specific transcription factors, DNA repair proteins, and chromatin-associated proteins. Our results in *Tetrahymena* are consistent with the role of SUMOylation in somatic nuclear processes such as the regulation of transcription, which is limited to the MAC in vegetative cells.

SUMOylation increases during conjugation in *T. thermophila*. Anti-Smt3p antibodies (Fig. 1C) were also utilized to determine SUMO expression throughout conjugation by Western blot analysis. Figure 2A shows schematic representations of the stages when protein was prepared for analysis. Figure 2B shows a typical SUMOylation pattern with several reactive bands consistent with a range of proteins conjugated to Smt3p. The image is from a short exposure to emphasize the difference in signal between vegetative cells and conjugating cells, but a longer exposure showed a larger number of bands in the vegetative protein samples. The arrowhead labeled Smt3p indicates the expected migration of free...
Smt3p. Experiments with high-percentage gels (20%) showed that Smt3p migrates with a mass of approximately 13.5 kDa, but on the 10% gel shown in Fig. 2B proteins below 20 kDa were not well resolved. A slightly higher apparent molecular mass than the theoretical molecular mass (11.4 kDa) of Smt3p is not surprising, as SUMO proteins have been reported to exhibit anomalously slow migration on SDS-PAGE gels (33). The high-molecular-mass bands observed at the 40- to 200-kDa range were Smt3p substrates that represented a diverse set of target proteins that are modified by Smt3p in vegetative and mating cells. In mating cells, we observed that Smt3p adduct formation increased as cells progressed through conjugation, with the highest signal observed between 7 and 10 h postmixing, which corresponded to anlagen formation, implicating SUMOylation in its role in MAC differentiation (Fig. 2A and B). The bar graph in Fig. 2C provides a quantitative assessment of the increased signal above 40 kDa relative to total protein as measured by Coomassie staining. This increase in Smt3p signal is consistent with microarray expression data, which show an increase in transcript levels during conjugation, including anlagen formation (27). These results demonstrate that SUMOylation occurs differentially between vegetative and mating Tetrahymena, with a peak in SUMO conjugates observed during MAC differentiation.

To determine the cellular location of the increased Smt3p, we performed immunofluorescence with the same anti-Smt3p antibody used in Fig. 2. Mating cells were fixed at various times during conjugation leading up to the beginning of MAC development (9 h). A low signal relative to background fluorescence masked specific localization in early stages of conjugation. As conjugation progressed, Smt3p was detected in parental MACs by the end of meiosis, and the antibody revealed a strong accumulation in the developing anlagen (Fig. 3). We also used the GFP-Smt3p-expressing strains (Fig. 1) and found that Smt3p first localized to parental MACs early in conjugation and later accumulated in the developing anlagen, which mimicked our results with the anti-Smt3p immunofluorescence analysis (Fig. 3). Both techniques showed that the signal in the parental MAC disappeared as the anlagen developed and before the MAC was degraded. We did not detect Smt3p in the micronuclei or meiotic products during conjugation using anti-Smt3p or GFP-Smt3p. Although the GFP-Smt3p strains have the disadvantage of expression from the inducible MTT1 promoter, the consistent results using antibodies and GFP fusions give us confidence in our observations.

In Paramecium, GFP-Uba2p localized to the developing MAC (20). Antibodies against Tetrahymena Uba2p are not available for immunofluorescence, but GFP-Uba2p was expressed from the inducible MTT1 promoter in the absence of wild-type Uba2p (described in Materials and Methods). As shown in Fig. 3, GFP-Uba2p is located in the old MAC during the meiotic “crescent” phase (prophase I) of conjugation. The signal remains in the old MAC at later stages of meiosis and, unlike Smt3p, Uba2p is clearly visible in the meiotic haploid products as shown in Fig. 3. The signal is also detectable in haploid products during the period of

![FIG 2](image-url) Differential modification of proteins by Smt3p during conjugation versus vegetative growth. (A) Schematic representation of the stages of conjugation at which cells were lysed. The following stages are shown: pair formation; pronuclear exchange; MAC differentiation; anlagen formation; exconjugants. (B) Whole-cell extracts (WCEs) were prepared from vegetative and mating B2086 and CU428 wild-type cells at 0, 2, 5, 7, 10, 24, and 30 h postmixing. WCEs were analyzed by 10% SDS-polyacrylamide gel electrophoresis followed by Coomassie blue staining (for loading control) (bottom panel) and Western blotting using polyclonal anti-Smt3p antibody (top panel). The arrowhead indicates the expected position of free Smt3p (~13 kDa) and high-molecular-mass proteins that are likely to be Smt3p conjugates. A Coomassie-stained gel was included as a control to evaluate equivalent sample loading. (C) The bar graph provides a quantitative assessment of the immunoblotting signal. The data are normalized for sample loading (Coomassie-stained gel).
pronuclear exchange (Fig. 3). As the developing MACs (anlagen) appear, they contain increasing Uba2p signal, and the signal is simultaneously reduced in the parental (old) MAC. Consistent with our observations in vegetative cells, the signal is not detected in micronuclei at the two-mic two-MAC stage of development. Interestingly, Paramecium GFP-Uba2 expressed from its endogenous promoter showed little signal in the parental MAC, and the primary signal appeared in the anlagen (20). The Tetrahymena Uba2p and Smt3p localization results (Fig. 3), along with the immunoblot assay results (Fig. 2), are consistent with a major increase in SUMOylation of nuclear proteins during conjugation, particularly in the developing MAC. The absence of GFP-Smt3p localization in the meiotic products, in contrast to the GFP-Uba2p localization to those structures, is not readily explained but it is clearly not an issue of protein abundance (the result was independent of the level of expression) or stability (since the signal in the MAC was robust).

Complete deletions of SMT3 and UBA2 result in cell lethality. In budding yeast and invertebrates such as the nematode Caenorhabditis elegans, there is a single SMT3 gene which is essential for viability (34, 35). Deletions in the SUMO-activating enzyme UBA2 or the SUMO-conjugating enzyme UBC9 are lethal in the budding yeast (11, 32, 35), C. elegans (34), A. thaliana (36), and in mice (37). In Paramecium tetraurelia, RNAi silencing of UBA2 or SUMO had no detectable effect on vegetative cells, but it arrested conjugating cells. To test whether SMT3 and UBA2 are essential genes in Tetrahymena, we generated micronuclear (germ line) deletion strains that were subsequently mated to produce complete (mic and MAC) deletions. The initial heterozygous mic knockout strains were selected with paromomycin after transformation with KO constructs containing the neomycin resistance cassette (neo3) flanked by sequences upstream and downstream of each coding region (Fig. 4A). The resulting heterozygous knockout cells were cultured without paromomycin selection to allow phenotypic assortment of the drug-resistant (KO) alleles and identification of paromomycin-sensitive cells with fully wild-type MACs. These heterozygous knockout cells were mated with “star” strains containing defective micronuclei and wild-type MACs. These crosses result in abortive conjugation, in which paired cells complete meiosis and exchange genetic material but separate without making new macronuclei. These postconjugation cells emerge with homoygous micronuclei but retain their original MACs, genetically wild type for SMT3 and UBA2 (Fig. 4A and B) (23). Phenotypically, these cell lines are paromomycin sensitive, but we used PCR amplification to identify the strains homoygous for the neo3 cassette in place of the corresponding coding region in the micronucleus (Fig. 4C). These homoygous heterokaryon knockout strains of SMT3 or UBA2 were then mated, and individual pairs were isolated to nutrient medium. Analysis of >100 pairs from each cross revealed that the majority of pairs failed to survive (Table 1). Pairs that did survive were tested for paromomycin resistance to determine whether they were true exconjugant progeny or pairs that aborted conjugation. This test was used because the parental strains were phenotypically paromomycin sensitive (MAC genotype) but their germ line micronuclei were homoygous for paromomycin resistance. The formation of a new MAC would result in paromomycin resistance. As indicated in Table 1, none of the surviving lines was paromomycin resistant, and most likely they were abortive mating pairs containing wild-type MACs. Control crosses of the same knockout heterokaryon strains with wild-type cells (B2086 or CU428) resulted in high survival (~93%) of true exconjugant progeny that were paromomycin...
resistant. This demonstrated that the knockout heterokaryons contain fertile micronuclei. The data are consistent with a lethal phenotype for complete deletions of SMT3 or UBA2. This has been reported in other organisms, and we conclude that both are essential genes in Tetrahymena.

Interestingly, there was a substantial difference in the timing of postconjugation death for \( \Delta SMT3 \) and \( \Delta UBA2 \) strains. \( \Delta SMT3 \) progeny died before the first postzygotic cell division, but \( \Delta UBA2 \) progeny died much later, 6 to 8 cell divisions after mating (~72 h postisolation). Clearly, UBA2 expression is not required from the vegetative macronucleus to complete conjugation. The SMT3 and UBA2 knockout heterokaryon crosses were monitored by DAPI staining to detect any grossly aberrant nuclear events (i.e., meiosis, pronuclear fusion, mitotic divisions, and anlagen development), but none was detected. The \( \Delta UBA2 \) vegetative progeny have the normal distribution of 1 MAC and 1 mic prior to death. The \( \Delta SMT3 \) progeny arrest in conjugation at the 2-MAC, 2-mic stage, but the events prior to that appear normal (data not shown). We also examined the \( \Delta SMT3 \) progeny and \( \Delta UBA2 \) progeny for defective programmed DNA elimination. Using a PCR strategy developed previously (38), we examined DNA from cells at the time of mixing (time zero) and 24 h later from several hundred conjugating pairs collected after mixing the same culture. A total of five eliminated DNA elements were examined for each cross. The results for the M and R elements in \( \Delta SMT3 \) progeny are shown in Fig. S1 in the supplemental material. For each eliminated element, the product expected for accurate DNA processing was detected and there was no evidence for the inhibition of DNA elimination. The explanation for the shorter life span of \( \Delta SMT3 \) cells compared with \( \Delta UBA2 \) is not clear but could result from faster depletion of parentally expressed Smt3p.

**Gene rescue with the MTT1 promoter converts SMT3 or UBA2 deletion lines into conditional mutants.** As SMT3 and UBA2 are essential genes, complete deletions resulted in cell death, making it difficult to obtain information on the null phenotype of these genes. This problem was circumvented by the creation of conditional mutants of SMT3 and UBA2 in which the expression of these genes could be regulated by addition of CdCl2 to the culture medium. As \( \Delta UBA2 \) progeny survive for up to 72 h postmixing, the parental UBA2 heterokaryons were mated en masse, and at 8 h postmixing (corresponding to formation of new anlagen), mating cells were biolistically transformed with the 

![FIG 4](https://example.com/figure4.png)
MTT1 control. For \( \Delta SMT3 \) mated cells, we were unable to rescue the lethal progeny with the GFP-SMT3 transgene, possibly due to insufficient expression of the introduced copies at the end of conjugation. To overcome this issue, we generated Tetrahymena cell lines that were somatic transformants expressing introduced FLAG-His6 epitope-tagged SMT3 (also driven by the MTT1 promoter) at the BTU1 locus in CU522 and CU725 strains. Incorporation at the BTU1 locus in these strains confers resistance against the drug paclitaxel; the strains are otherwise paclitaxel sensitive. Next, we transformed these FLAG-His6-SMT3-expressing strains with the neo3 knockout construct (again under the control of the MTT1 promoter), disrupting the endogenous SMT3 gene. These conditional SMT3 cells were scored for growth as described for panel A. (C) RT-PCRs to detect wild-type (wt) SMT3 transcripts in conditional mutants. The locations of the primers (arrows) used to amplify regions from the cDNA are shown on the left. Lanes 1, 2, and 3 on the gel correspond to PCR products with the primer sets (1, 2, and 3) indicated on the diagrams to the left. No wt SMT3 transcript was detected in the SMT3 conditional mutant cell line.

**FIG 5** Tetrahymena expressing the GFP-UBA2 or FLAG-His\(_6\)-SMT3 transgene regulated by the MTT1 promoter behave as conditional mutants. (A) Schematic drawing of \( \Delta UBA2 \) homozygous heterokaryon strains that were mated and transformed with the GFP-UBA2 transgene regulated by the MTT1 promoter and inserted at the rpl29 locus. The resulting UBA2 conditional cell lines and wild-type CU428 strains were grown vegetatively and transferred into 10 ml of SPP medium at an initial concentration of 200 cells/ml with either 0.1 \( \mu \)g/ml cadmium or no cadmium. At 0, 4, 8, 12, 20, 24, and 48 h after placement in growth medium, cells were fixed and scored using a hemocytometer. (B) \( \Delta SMT3 \) homozygous homokaryon progeny were lethal within 24 h, and therefore a different approach was used to generate a conditional mutant expressing SMT3. The schematic drawing shows the transformation of strain CU522 with MTT1-driven FLAG-His6-SMT3 at the BTU1 locus. The same strain was then transformed with the neo3 knockout construct (again under the control of the MTT1 promoter), disrupting the endogenous SMT3 gene. These conditional SMT3 cells were scored for growth as described for panel A. (C) RT-PCRs to detect wild-type (wt) SMT3 transcripts in conditional mutants. The locations of the primers (arrows) used to amplify regions from the cDNA are shown on the left. Lanes 1, 2, and 3 on the gel correspond to PCR products with the primer sets (1, 2, and 3) indicated on the diagrams to the left. No wt SMT3 transcript was detected in the SMT3 conditional mutant cell line.
SMT3 and UBA2 requirement in mating pair formation in conjugating cells. We know from previous studies in Paramecium tetraurelia that silencing UBA2 results in conjugation arrest during MAC development (20). Using our conditional Smt3p and Uba2p cell lines, we tested the effect of Smt3p or Uba2p depletion on conjugation in Tetrahymena. Conditional mutants of different mating types were cultured overnight in nutrient medium with or without cadmium to early log phase and then starved in starvation buffer under the corresponding plus or minus cadmium condition (see Materials and Methods for details). A portion of each –Cd culture was supplemented with 0.1 μg/ml cadmium 2 h prior to mating; these cultures are referred to as +Cd addition. Cells were then mixed to initiate mating. (B) At 8 h postmixing, cells were fixed and scored using a hemocytometer to calculate mating efficiency. Smt3p and Uba2p conditional mutants cultured under cadmium-deficient conditions (–Cd) were unable to form mating pairs and did not progress through conjugation. Cells from +Cd cultures or –Cd cultures that were supplemented with cadmium 2 h prior to mixing (+Cd addition) formed mating pairs. Smt3p, SMT3 conditional mutant; Uba2p, UBA2 conditional mutant. Error bars (standard errors) are shown.

DISCUSSION

Developmentally regulated SUMOylation during conjugation in Tetrahymena. Global increases in SUMOylation are known to result from exposure to environmental conditions or specific reagents, for example, hydroxyurea, heat shock, or ethanol (43, 47, 48). In contrast, few examples of large developmentally regulated increases in SUMOylation have been reported. Our study revealed that the sexual cycle of Tetrahymena is one such example. Immunoblot analysis of whole-cell extracts revealed differential modification of substrates by Smt3p between vegetative and mating Tetrahymena cultures (Fig. 2). Smt3p increased as conjugation progressed, with the highest Smt3p signal observed during the MAC differentiation stage. This increase is consistent with elevated SMT3 and UBA2 transcript levels in conjugating cells compared with vegetative or starved cells (20). Our immunofluorescence studies also showed that Smt3p is predominantly a nuclear protein during the MAC development stage (Fig. 3). Together, the...
immunoblotting and immunofluorescence data suggest a requirement for protein SUMOylation inside the developing MAC. During this period, extensive genome remodeling occurs, including heterochromatin formation, transcriptional regulation, DNA replication, and DNA repair (19, 49), processes that have known evidence for SUMOylation in other species. In addition, our previous study of UBA2 and SUMO genes in Paramecium revealed elevated transcript levels for both during conjugation. RNAi-generated knockdowns arrested conjugating cells and inhibited programmed DNA elimination (20). While the nuclear events in Tetrahymena and Paramecium are dramatic, other reports of global changes in SUMOylation are known. During mouse spermatogenesis, two distinct expression profiles of SUMO isoforms are detected, one during meiosis and the other in postmeiotic spermatids, suggesting an important role for SUMOylation in spermiogenesis (29). A recent study in human keratinocyte differentiation also highlighted SUMOylation as a regulator of cell differentiation. In these cells, SUMO expression was upregulated by calcium signaling at both the RNA and protein levels, while degradation of SUMO-activating and -conjugating enzymes resulted in abnormal differentiation of these cells, demonstrating key roles for SUMOylation in the keratinocyte differentiation process (50).

The SUMO pathway is conserved in Tetrahymena. Despite the dramatic changes in SUMOylation in Tetrahymena, we found that most features of the pathway are conserved with other eukaryotes. As expected based on other species, the localization of Smt3p and Uba2p is predominantly nuclear (reviewed in reference 33). In vegetative Tetrahymena cells, both Smt3p and Uba2p localized to the somatic MAC (Fig. 1). Interestingly, we did not observe a GFP-Uba2p or GFP-Smt3p signal in the mic, nor did we detect the loss of mics in our conditional cell lines. We examined more than 50 cells during various stages of mitosis and could not detect a GFP-Smt3p signal from the micronucleus (data not shown). We cannot claim that Smt3p is completely absent from the mic, but our data support a much lower concentration in mics than in MACs during vegetative growth.

As is true for other eukaryotes, UBA2 and SMT3 are essential genes. We generated germ line deletions of the SMT3 and UBA2 genes by using homologous recombination. The deletions were carried in the mics of heterokaryon cell lines that express wildtype SMT3 and UBA2 from the somatic MAC. The progeny of these heterokaryon cells had complete deletions of SMT3 or UBA2 and died following conjugation (Table 1). This lethal phenotype is consistent with the deletion of SUMO and UBA2 genes in yeast (32, 51) and mammalian model systems (37). Interestingly, our earlier work with the ciliate Paramecium showed that RNAi knockdown of SMT3 and UBA2 had no effect on vegetative growth (20). In retrospect, this lack of vegetative phenotype is likely due to incomplete knockdown providing a low level of SMT3 and UBA2 expression. As observed for other eukaryotes, Tetrahymena Smt3p- and Uba2p-depleted cell lines were hypersensitive to DNA-damaging agents. When we treated Tetrahymena with MMS or cisplatin, cells depleted for Smt3p and Uba2p showed increased sensitivity to both DNA-damaging agents (Fig. 7). Several proteins involved in DNA repair are SUMO substrates or proteins that interact with components of the SUMO pathway (42, 43, 52). Examples include DNA repair proteins, such as PCNA (40), 53BP1 and MDC1 (42), and XRCC4 (52). 53BP1 and MDC1 localize along with SUMO proteins to sites of double-strand breaks that occur as a result of DNA damage (42). XRCC4, an important protein in the mammalian nonhomologous end-joining (NHEJ) pathway, depends upon transient SUMOylation for localization to the nucleus (52). The NHEJ pathway is believed to be the key mechanism for repair of double-stranded DNA (dsDNA) breaks generated during programmed DNA rearrangements that occur naturally during conjugation in ciliates (15). In Paramecium tetraurelia, the RNAi-induced silencing of ligase IV (a partner of XRCC4 in NHEJ) during conjugation results in the persistence of free broken ends during genome reorganization (53). The increasing links between NHEJ pathway proteins and genome reorganization during ciliate conjugation suggest potential targets for SUMOylation. The increased sensitivity of conditional Smt3p mutants to DNA-damaging agents along with the accumulation of Smt3p and Uba2p in the MAC anlagen are consistent with a role for SUMOylation during MAC differentiation in ciliates.

The SUMOylation pathway is required for cell pairing. When we reduced Uba2p expression levels in conditional mutant strains by withdrawing cadmium, the cells were unable to form conjugating pairs. The same conditional strains growing in the presence of cadmium proceeded through conjugation normally, as did wild-type cells. Although this result was unexpected, there is precedence for SUMOylation-dependent effects on mating. In the budding yeast, SUMO modification of transcription factor Ste12 is stimulated by mating pheromone, thus increasing its half-life and committing the cell to the mating differentiation program (54). In
addition, turnover of the yeast mating type factor α1 protein is dependent on SUMO-targeted ubiquitin ligases SLX5 and SLX8, which is consistent with the involvement of SUMO-mediated pathways (55). In our system, the inability of Smt3p- and Uba2p-deficient Tetrahymena cells to form pairs could result from altered gene transcription, modified signaling pathways, or direct SUMOylation of the mating-type protein. The experiments presented here do not allow us to distinguish between direct and indirect SUMO-mediated effects, but the recent identification of the mating-type protein from Tetrahymena provides an opportunity to test some of these possibilities in the future (56). The dramatic upregulation of SUMOylation in Tetrahymena, coupled with the defined events of genome alteration (heterochromatin formation, DNA elimination, DNA replication) make this a rich system for analysis of SUMOylation function and dynamics. Although the cell-pairing defect prevented the use of these lines to analyze defects at later stages of conjugation, we expect strong phenotypes during macrocyclic development. Efforts are currently focused on developing alternative approaches, such as inducible RNAi knockdowns of SUMO pathway genes and identification of SUMOylated proteins specific to conjugation for further analysis.

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