Phospho-site mutants of the RNA Polymerase II C-terminal domain alter subtelomeric gene expression and chromatin modification state in fission yeast

Maki Inada1,*, Robert J. Nichols1, Jahan-Yar Parsa2, Christina M. Homer2, Ruby A. Benn1, Reyal S. Hoxie1, Hiten D. Madhani1, Stewart Shuman3, Beate Schwer4 and Jeffrey A. Pleiss5,*

1Biology Department, Ithaca College, Ithaca, NY 14850, USA, 2Department of Biochemistry and Biophysics, UCSF, San Francisco, CA 94158, USA, 3Molecular Biology Program, Sloan-Kettering Institute, New York, NY 10065, USA, 4Department of Microbiology, Weill Cornell Medical College, New York, NY 10065, USA and 5Department of Molecular Biology and Genetics, Cornell University, Ithaca, NY 14853, USA

Received January 21, 2016; Revised June 21, 2016; Accepted June 23, 2016

ABSTRACT

Eukaryotic gene expression requires that RNA Polymerase II (RNAP II) gain access to DNA in the context of chromatin. The C-terminal domain (CTD) of RNAP II recruits chromatin modifying enzymes to promoters, allowing for transcription initiation or repression. Specific CTD phosphorylation marks facilitate recruitment of chromatin modifiers, transcriptional regulators, and RNA processing factors during the transcription cycle. However, the readable code for recruiting such factors is still not fully defined and how CTD modifications affect related families of genes or regional gene expression is not well understood. Here, we examine the effects of manipulating the Y1S2P3T4S5P6S7 heptapeptide repeat of the CTD of RNAP II in Schizosaccharomyces pombe by substituting non-phosphorylatable alanines for Ser2 and/or Ser7 and the phosphomimetic glutamic acid for Ser7. Global gene expression analyses were conducted using splicing-sensitive microarrays and validated via RT-qPCR. The CTD mutations did not affect pre-mRNA splicing or snRNA levels. Rather, the data revealed upregulation of subtelomeric genes and alteration of the repressive histone H3 lysine 9 methylation (H3K9me) landscape. The data further indicate that H3K9me and expression status are not fully correlated, suggestive of CTD-dependent subtelomeric repression mechanisms that act independently of H3K9me levels.

INTRODUCTION

The C-terminal domain (CTD) of the Rpb1 subunit of RNA Polymerase II (RNAP II) plays key roles in regulating gene expression (1). In humans and mice, the CTD consists of 52 heptapeptide repeats of the consensus sequence Y1S2P3T4S5P6S7, or variants thereof. The CTDs of the fission yeast Schizosaccharomyces pombe and the budding yeast Saccharomyces cerevisiae comprise 29 and 26 heptad repeats, respectively, suggesting that the length of the CTD repeat array may be correlated with complexity of the organism (2). The CTD heptads are dynamically modified during the transcription cycle (3). The phosphorylation and dephosphorylation of serines 2, 5 and 7, threonine 4, and tyrosine 1, along with cis-trans isomerization of prolines 3 and 6, allow for a vast combinatorial complexity of CTD primary structures that inscribe a readable ‘code’ to orchestrate recruitment, activity, and egress of numerous cellular factors that govern gene expression (2).

Different phosphorylation or modification states of the CTD have been shown to play important roles in coordinating the coupling of RNA processing pathways. For example, RNAP II recruits to its CTD histone methyltransferases that generate the relaxed chromatin necessary for transcription initiation (2,3). Phosphorylation of Ser5 recruits enzymes that cap the 5′ end of nascent mRNAs. Indeed, in fission yeast, fusion of the capping enzymes RNA triphosphatase and RNA guanylyltransferase to RNAP II can rescue the lethality of mutants unable to be phosphorylated at Ser5, indicating that the chief essential function of Ser5 phosphorylation is the recruitment of the capping machinery (4). Ser2 and Ser5 phosphorylations are important in directing co-transcriptional methylation of lysines 4 and 36 of the histone H3 (5).
During transcription elongation, Ser2 phosphorylation levels increase, and these have been shown to be important for recruitment of splicing factors such as Prp40, U2AF65 and U2 snRNA (6,7). Others have followed this finding by demonstrating splicing defects of specific reporter introns in human U2OS cells and chicken DT40 cells containing S2A mutations (8,9). Whereas global effects of the S2A mutation on gene expression have been examined previously (10–12), the methods used were not optimized to examine splicing, leaving unknown the full extent of the genome-wide impact of Ser2 phosphorylation on splicing. Here we used splicing-sensitive microarrays to examine pre-mRNA splicing in S. pombe cells mutated at CTD phosphorylation sites Ser2 and/or Ser7. Our results weigh against a role for CTD Ser2/7 phosphorylation in pre-mRNA splicing, but reveal an unexpected relationship with chromatin modification and gene expression in the subtelomeric regions of the genome.

MATERIALS AND METHODS

Cell growth

Strains were inoculated in 5 ml of YES medium and grown to saturation at 30°C. Saturated cultures were backdiluted in 25 ml of YES medium and grown to mid-log phase (A600 between 0.4 and 0.7), flash frozen in liquid nitrogen then stored at −80°C.

Total RNA isolation, cDNA synthesis and microarray hybridization

Total RNA was isolated, converted to cDNA by reverse transcription, and labeled for microarray hybridization as described previously (13). Microarray probes were designed such that each protein coding gene was targeted by a single exonic probe (5098 in total). In addition, probes were designed targeting every annotated intron in the genome (4885 in total) as well as the junctions resulting from re-designed targeting every annotated intron in the genome.

Chromatin immunoprecipitation

Chromatin immunoprecipitation

Cultures (50 ml) of S. pombe were grown at 30°C to A600 = 1.0 and crosslinked by addition of formaldehyde (Sigma) to a final concentration of 1% with incubation at room temperature for 15 min. The crosslinking reaction was stopped with the addition of 125 mM glycine for 5 min. Cells were washed twice in 1× TBS (20 mM Tris–HCl, pH 7.6, 0.15 M NaCl) and snap frozen. Samples were resuspended in 500 μl ChIP lysis buffer (50 mM HEPES–KOH, pH 7.5, 140 mM NaCl, 1 mM EDTA, 1% Triton X-100, 0.1% sodium deoxycholate, and 1× EDTA-free Complete protease inhibitor (Roche)) and were lysed in a Mini-Beadbeater (BioSpec Products) for 7 cycles of 1 min each with 2 min rests on ice. The cell lysate was transferred to a new tube and centrifuged for 10 min at 7000g at 4°C. The resulting chromatin pellet was resuspended in 300 μl ChIP lysis buffer and sonicated for four 15 min cycles (High setting; 30 s on, 1 min off) in a Bioruptor waterbath sonicator (Diagenode). Cell debris was then removed by centrifugation at 21 000g for 10 min at 4°C and the supernatant was brought to 1.5 ml in ChIP lysis buffer. Immunoprecipitation was performed at 4°C overnight in 500 μl chromatin aliquots using 2 μg anti-H3K9me2 antibody (ab1220, Abcam). Pre-washed Protein
A Dynabeads (30 μl, Invitrogen) were used to bind the antibodies. Following a 2 h incubation at 4°C, the beads were washed twice with 1 ml ChIP lysis buffer, twice with 1 ml high salt ChIP lysis buffer (ChIP lysis buffer with 500 mM NaCl), twice with 1 ml wash buffer (10 mM Tris–HCl, pH 8.0, 0.25 M LiCl, 0.5% NP-40, 0.5% sodium deoxycholate, 1 mM EDTA), and once with 1 ml TE buffer (10 mM Tris–HCl, pH 8.0, 1 mM EDTA). Each wash was performed for 5 min at room temperature with rotation. Beads were eluted with 100 μl elution buffer (50 mM Tris–HCl, pH 8.0, 10 mM EDTA, 1% SDS) at 70°C for 20 min, followed by a second elution at room temperature for 5 min with 150 μl TE buffer with 0.67% SDS and 334 μg/ml proteinase K (Sigma). Input samples (50 μl) were combined with 200 μl TE buffer with 1% SDS and 250 μg/ml proteinase K. All samples were incubated overnight at 65°C, followed by addition of 1250 μl buffer NTB and DNA purification using a NucleoSpin Gel Clean-up column (Macherey-Nagel).

ChIP-seq library construction

For each genotype, library construction was performed for two biological replicates. Immunoprecipitation reactions or input samples were processed by treatment with the End-It DNA End-Repair Kit (Epicentre) and then A-tailed using Klenow fragment (New England Biolabs) according to manufacturers’ instructions, with column purifications after each step using a NucleoSpin Gel Clean-up column (Marchery-Nagel) and MinElute Reaction Clean Up Kit (Qiagen) respectively. Next, barcoded Illumina adaptors (35 nM) were ligated to the DNA using 1200 U Rapid T4 DNA Ligase (Enzymatics) in a 30 μl reaction with incubation at room temperature for 30 min. The DNA was column purified using a NucleoSpin Gel Clean-up column (Marchery-Nagel) and PCR amplified using 1 U Phusion DNA polymerase (New England Biolabs), 2 M betaine, 75 μM dNTPs, and 0.4 μM each primer (TruSeq PCR enrichment primers Forward: 5’-AATGATACGGCGACACGATACG-3’; Reverse: 5’-CAAGCAGAAGACGGCATACGAG-3’) in a 50 μl reaction. Cycling conditions were: 98°C for 3 min, followed by 15 cycles of 98°C for 1 min 20 s, 65°C for 30 s, and 72°C for 30 s, with a final step of 72°C for 5 min. The reaction was size selected for products between 200 and 350 bp using SPRI beads (15). Library quality was determined by High Sensitivity DNA Bioanalyzer analysis (Agilent).

Sequencing data processing, read alignment and subtelomeric region analysis

ChIP-seq data were aligned using Bowtie (16). We allowed no mismatches within the seed sequence and, if a read could align equally well to multiple loci, a locus was chosen at random. Indexed, sorted bam files were created for each dataset using SAMtools (17) and bedgraph files were created using BEDTools (18). Using the bedgraph file, a sliding window algorithm was applied that averaged coverage over a 1000 bp window. This smoothed bedgraph was used for all downstream analysis.

The background signal level was defined as average coverage in all regions of the genome excluding the 80 kb adjacent to each chromosome end and the centromeric regions. Telomeric and subtelomeric regions (80 kb adjacent to chromosome ends) were compared between datasets by normalizing each sample’s coverage, on a per-base basis, to that of an input sample, consistent with field standards (19). To control for differences in read count, each sample was further normalized such that its background signal level (as defined above) would equal that of the input sample. This value corresponds to 1.0 in the plots.

Data availability

Microarray and ChIP-seq data are available through NCBI’s GEO database (http://www.ncbi.nlm.nih.gov/geo/) using accession number GSE83426.

RESULTS

Global analyses using splicing-sensitive microarrays reveal changes in gene expression but not splicing in rpb1-CTD-Ser7 mutants

To examine the role of CTD serine phosphorylation marks on pre-mRNA splicing and global gene expression, we took advantage of rpb1-CTD mutant strains of S. pombe in which non-phosphorylatable alanines were substituted for every Ser2 (S2A4), Ser7 (S7A) or both (S2A/S7A) in the context of a fully functional Rpb1 CTD array (comprising 14 consensus heptad repeats linked to the body of Rpb1 by a “rump” consisting of four degenerate heptads) (4). In addition, a fourth mutant in which each Ser7 was substituted by the phosphomimetic glutamic acid (S7E) was studied (4).

RNAseq has been employed previously to analyze changes in gene expression for a subset of these CTD mutants and no overt splicing defects were reported (12). However, while RNAseq is superior to microarrays for de novo discovery of introns, the low read depths typically obtained for either exon-exon or exon-intron boundaries can hinder meaningful quantitative analyses of genome-wide changes in splicing efficiency. Therefore, the genome-wide effects of these CTD mutations were examined here using custom-designed, splicing-sensitive microarrays that assay changes in gene expression for all annotated protein-coding genes in S. pombe, while simultaneously assaying splicing efficiency for every known intron in the genome (13). For each of the four CTD mutants, multiple replicate arrays were performed comparing relative RNA levels in the mutant and WT strains (see Materials and Methods). As a basis of comparison, we also examined the splicing defect associated with a mutation in the prp2 gene, the S. pombe homolog of U2AF-65, which had been previously examined using this same microarray platform (20). As seen in Figure 1, none of the CTD mutants showed a global defect in splicing. The data, which are displayed in groups of three (total mRNA, pre-mRNA and mRNA) for each of the mutants, were arranged such that the ~4800 splicing events were ordered by the behavior of the pre-mRNA species, with those showing the largest increase appearing at the top and those with the largest decrease at the bottom. As expected, when examining the prp2-1 data, pre-mRNA accumulation can be detected for the majority of introns in the genome. Accumulation of the pre-mRNA species in this mutant is accompanied, in most cases, by a decrease in the level of mature...
Figure 1. Effect of rpb1-CTD mutants on splicing. Genome-wide changes in pre-mRNA splicing for rpb1-CTD mutant strains S2A, S7A, S2A/S7A, and S7E compared to the isogenic WT strain were measured for ~4800 introns via splicing-sensitive microarray analyses, and compared to the canonical splicing factor mutant strain prp2-1. Microarray data are displayed as Total mRNA (T), pre-mRNA (P), and mature mRNA (M) groupings for each strain. The data are ordered by largest to smallest accumulation of the pre-mRNA species. Insets show the top six pre-mRNA species for each strain.

mRNA, consistent with the prp2-1 allele causing a bona fide splicing defect. By contrast, very few pre-mRNAs accumulated in the rpb1-CTD mutants. Moreover, as seen in the top insets of Figure 1, for the relatively small proportion of transcripts for which the pre-mRNA levels did increase in the rpb1-CTD mutants, the majority showed a simultaneous increase in the level of mature mRNA. These data suggest an overall increase in transcription rather than a change in splicing efficiency for these genes.

Spliceosomal U snRNA levels are unaffected by CTD Ser2 or Ser7 mutations

Prior studies had shown that mutations in the CTD, specifically substitutions at Ser7, affected the processing and steady-state levels of U2 snRNA in human cells (21). The microarray platform, which included probes targeting many non-coding RNAs, allowed us to monitor changes in the levels of U snRNAs in the CTD mutant strains. We found that there was little change in the levels of U1, U2, U4, U5 and U6 snRNAs in the rpb1-CTD mutant strains (Supplemental Figure S1).

Global analyses of gene expression in rpb1-CTD-Ser2 and -Ser7 mutant strains

To characterize global changes in gene expression, we used the Significance Analysis of Microarrays (SAM) tool to identify transcripts with significantly different changes in gene expression in the replicate datasets of each of these mutants (22). Because SAM assesses the statistical significance of a change without necessarily considering the biological significance of those changes, we further restricted our analyses to those transcripts which both satisfied the SAM significance test and were at least two-fold changed in their overall gene expression. By these criteria, each of the mutants caused statistically significant changes in gene expression: a total of 192 genes were misregulated in the S2A mutant, 167 in the S2A/S7A mutant, 57 in the S7A mutant, and 137 in the S7E mutant (Supplemental Table S1). That more genes were misregulated in S2A, S2A/S7A, and S7E than in S7A correlates with the observations that S7A cells exhibited no discernible growth defect at temperatures between 18 and 37°C, whereas the other mutants did exhibit cold-sensitive or heat-sensitive growth defects (4). In general, increases in gene expression outnumbered decreases in
gene expression. Moreover, significant overlap of gene expression targets was seen between the different mutants, in particular for S2A and S2A/S7A, which share more than half of their respective targets (Figure 2).

Comparison of microarray gene expression data with RNAseq data

Global gene expression can be monitored by microarray and RNAseq analyses and although the correlations seen between datasets generated by these two approaches might be limited based on many considerations (23,24), we sought to compare prior RNAseq data available for a subset of the CTD mutants (12) to our microarray data, which also include the S7E strain. In spite of technical differences in processing the samples (e.g. the use of total RNA versus poly(A)+ RNA), reasonable correlations were seen between the RNAseq and microarray datasets comparing WT and S2A strains (Pearson correlation coefficient of 0.54), as well as the WT and S2A/S7A strains (Pearson correlation coefficient of 0.59). Likely owing to the smaller number of genes showing misregulation in S7A, a lower correlation was seen for these datasets (Pearson correlation coefficient of 0.40). When only considering sets of genes that were identified as being statistically significantly misregulated by the two approaches, the correlation was high. For the WT versus S2A comparison, of the 155 genes that were identified in this work as significantly misregulated and for which RNAseq data were available, 61 genes (40%) were identified as significantly misregulated by RNAseq. For the WT versus S2A/S7A comparison, 55 out of the 114 genes (48%) were in common, and for the WT versus S7A comparison, 16 out of the 41 genes (39%) were found in common. Nearly half of the genes that were identified in our study as being significantly misregulated but which were not called significantly misregulated in the RNAseq dataset were characterized by low numbers of RNA-seq reads (Supplemental Table S2). Further characterizations of the similarities and differences seen between our data and the published RNAseq data are described below.

Global analyses of genes with altered expression in the rpb1-CTD mutants reveal limited enrichment by Gene Ontology

The protein-coding genes affected by the Rpb1-CTD mutations were examined to identify enrichment of functional gene categories as defined by Gene Ontology (GO) analysis. The sets of genes that were either significantly upregulated or downregulated by our SAM analyses for each mutant strain were compared to the background distribution. Whereas some functional categories were identified by this approach (see Supplemental Table S3), overall the analysis failed to identify large groups of functionally related transcripts. For those categories that showed statistically significant over-representation, only a small number of specific transcripts were identified, leaving the misregulated expression of most transcripts unexplained from a functional perspective. An earlier RNAseq-based analysis of some of these same mutants in *S. pombe* reported changes in functionally related clusters of affected genes including meiotic genes, iron response genes, and phosphate homeostasis genes (12). Although these multi-gene pathways did not exhibit overall enrichment within our dataset, an examination of the behavior of specific transcripts within these GO categories between the two datasets revealed broad overlap (Supplemental Tables S2 and S3), largely reflecting the overall similarities described above for these datasets. For exam-
ple, the meiotic genes *ste11* and *mei2* that were previously demonstrated by Northern analysis to be affected by serine phospho-site mutations (4), were also misregulated within our data, showing decreased expression in the S2A mutant, increased expression in the S7A and S7E mutants, but intermediate levels in the S2A/S7A double mutant (Supplemental Figure S2).

**Gene expression in subtelomeric regions is specifically affected by RNAP II CTD mutants**

While examining the functions of the genes for which expression was impacted by the CTD mutations, it became apparent that a number of galactose response genes were upregulated in the S2A strain, notwithstanding that the cells from which the RNA was isolated were grown in glucose-containing medium. Indeed, four out of six galactose response genes (*gal1, gal7, gal10* and *SPBPB2B2.11*) showed significant upregulation in at least one of the four CTD mutants. We noticed that these four upregulated genes were located next to one another, and quite close to the right end of chromosome 2, suggesting that their increased expression could be a consequence of their similar chromosomal locations rather than any functional relationship.

To examine whether chromosomal location was broadly correlated with changes in gene expression resulting from the CTD mutations, sliding windows of gene expression changes were determined by averaging the log2 ratio of mutant vs WT expression values for every coding transcript in 10 kbp windows along each chromosome. As seen in Figure 3A, patterns of upregulated gene expression were apparent near the ends of chromosomes 1 and 2 for all four CTD mutants: statistically significant upregulation is seen for the 50–100 kb from the ends except for that of the right arm of chromosome 1 for the S7A and S2A/S7A mutants. Whereas increased gene expression was not observed for either arm of chromosome 3, the ends of chromosome 3 in *S. pombe* are different from chromosomes 1 and 2 in that they comprise arrays of repeated rDNA, which are typically transcribed by RNA polymerase I. On chromosomes 1 and 2, the regions of upregulation were large, extending ~50–100 kb from the telomeric ends of the chromosomes, and perhaps defining the subtelomeric regions of these chromosomes (Figure 3B). As shown in Figure 3B, large regions with downregulated gene expression were also observed on chromosomes 1 and 2 immediately adjacent to the regions of upregulation, ranging in size from ~25 to 80 kb and present on all but the right arm of chromosome 2. In contrast to these subtelomeric regions, the gene expression values across the remainder of the chromosomes were generally unchanged from WT, with only few exceptions.

Previous studies of global gene expression changes of rpb1-CTD mutants in *S. pombe* via microarray analyses did not describe region-specific changes in gene expression (10,11). By independently examining the data from these studies, we detected similar increases in subtelomeric gene expression in the Saberianfar et al. data at the ends of chromosomes 1 and 2, but not chromosome 3 for the S2A mutant, the one allele common to all experiments (Supplemental Figure S3).

**Validation of gene expression changes by quantitative RT-qPCR**

Reverse transcription and quantitative PCR (RT-qPCR) analyses were performed to validate the changes in expression detected by microarray. Primers were designed targeting two or more genes within the subtelomeric regions of each arm for chromosomes 1, 2 and 3 that were within 50 kb from the end of the chromosome (Supplemental Table S4). In addition, genes outside of the subtelomeric regions for chromosomes 1 and 2 were examined. The RT-qPCR data confirmed significant upregulation of genes in the subtelomeric regions for each of the four CTD mutants, whereas expression of the non-subtelomeric genes were unchanged compared to WT (Figure 4 and Supplemental Figure S4). We further used RT-qPCR to examine changes in expression of the meiotically regulated genes *ste11* and *mei2*, each of which had been previously shown to misregulate in the context of CTD mutants (4). The RT-qPCR data corroborated both our microarray data and the previ-
Figure 4. Effects of rpb1-CTD mutations on gene expression of individual genes by microarray and RT-qPCR analyses. Total mRNA levels for selected genes found to be upregulated within the 50 kb subtelomeric region by microarray analyses, as well as genes selected from the non-subtelomeric regions, were measured in the CTD mutants and compared to the WT strain by RT-qPCR analyses (see also Supplemental Figure S4). The log2 ratio of mutant vs WT were plotted for chromosomes 1, 2 and 3 for both microarray ($n$ = 3–5) and RT-qPCR ($n$ = 2) data. For the RT-qPCR experiments, gene expression levels were all normalized to act1 mRNA levels.

Previously published data, showing that ste11 and mei2 mRNA levels were decreased in the S2A strain, increased in the S7A strain, and near WT levels in the S2A/S7A strain. Importantly, these changes in gene expression match the known sterility phenotype of the S2A mutant that is reversed by the double mutant S2A/S7A (Supplemental Figure S2) (4).

Chromatin modifications are altered near the ends of the chromosomes

The telomeric and subtelomeric regions of chromosomes are typically heterochromatic, facilitating repression of gene expression in these regions. Given the increases in gene expression in these regions that accompanied the CTD mutations, we were interested in investigating whether changes in chromatin structure might be involved. ChIP-Seq was performed to query whether the repressive heterochromatin mark H3K9 methylation was altered in the rpb1-CTD mutant strains compared to WT. Consistent with our gene expression results, in the S2A mutant a general decrease in the H3K9 methylation levels was observed at the ends of chromosomes 1 and 2, but not chromosome 3 (Figure 5 and data not shown). The decrease in the H3K9 repressive marks appears within the first ∼20 to ∼45 kb from the chromoso-
mal ends; by contrast, the regions of increased gene expression observed by microarray were larger, ranging from ∼50 to ∼100 kb (Figures 3B and 5). Nevertheless, genes with decreased H3K9 methylation overlap genes with increased gene expression in the subtelomeric regions in our mutant strains (P<0.001, Fishers Exact). Each of the other CTD mutations tested also altered the pattern of H3K9me, but in more complex ways. The S7A allele produced no clear decreases in H3K9me, but rather an increase in a subtelomeric region on right arm of chromosome 1. A similar phenotype has been reported in the leo1Δ mutant, which encodes a subunit of the PAF1 elongation complex (25). The S7E and S2A/S7A mutants produced mixed effects with increases at some sites and decreases at other (Figure 5). While the correlation between H3K9 methylation state and gene expression level were significant, there were also numerous regions of divergence. For example, for the regions directly adjacent to the telomere on the left arm of chromosome 1 and the right arm of chromosome 2, H3K9 methylation levels were higher than WT for the S2A, S7E, and S2A/S7A mutants. However, gene expression within these regions was derepressed in the mutant despite the increased levels of the repressive H3K9 mark (Figure 5). These data indicate that the CTD mutants impact subtelomeric repression mechanisms beyond those determined by H3K9me levels.

**DISCUSSION**

Our initial motivation in this work was to interrogate the relationship between CTD phosphorylation state and pre-mRNA splicing efficiency. Numerous lines of evidence over the past several years have demonstrated the co-transcriptional nature of pre-mRNA splicing (26). Whereas several reports have suggested that this may be facilitated by direct interactions between the CTD and specific splicing factors, others have cast doubt upon these direct connections (27,28). Using splicing-sensitive microarrays to assess the pre-mRNA splicing efficiency of nearly every annotated splicing event in the fission yeast genome, we detected almost no defect in pre-mRNA splicing in the background of any of the mutants examined (Figure 1). Although small numbers of splicing events can be identified that show weak apparent defects in splicing efficiency, from a global perspective these data strongly support the conclusion that phosphorylation of Ser2 or Ser7 in the S. pombe CTD is not required for efficient pre-mRNA splicing genome-wide.

Absent defects in pre-mRNA splicing, we queried changes in gene expression. Several of the mutants examined here have been studied by others using either microarrays or RNA-Seq (4,10–12). Overall, the global changes in gene expression detected here were reasonably well-correlated with those seen in previous studies, particularly given the differences in detection platform and sample processing (Pearson correlations between 0.4 and 0.59). As with previous studies, our data demonstrated mis-regulation of several genes involved in iron response, phosphate homeostasis, and meiosis. Nevertheless, a global analysis of the gene ontologies associated with regulated transcripts failed to provide a compelling functional relationship between mis-regulated transcripts. While the GO analysis did identify a handful of enriched functional categories, the total number of transcripts contained within these categories represented only a fraction of the total transcripts misregulated by these mutants. Together, these data suggest that the changes in gene expression caused by these CTD mutations cannot be readily explained by alterations in functionally-related transcripts.

A common trend among many of the genes we found to be significantly upregulated in our genome-wide microarray experiment was their location within their chromosomes. Many of the genes we identified were clustered near the ends of chromosomes 1 and 2 (Figure 3). These areas may define a functionally distinct so-called subtelomeric region of their respective chromosomes. Chromosome 3 in S. pombe has a different structure than the other two chromosomes in that ribosomal RNA gene repeats exist near the ends of chromosome 3, perhaps explaining the distinct expression patterns seen in the CTD mutants for chromosomes 1 and 2, but not chromosome 3. Other groups have examined global changes in gene expression in the S2A mutant in S. pombe (10,11), albeit using different experimental platforms. While these studies identified and discussed expression changes in genes involved in cytokinesis and meiosis respectively, our analysis of the data generated by Saberianfar et al. show an up-regulation of genes in the subtelomeric regions of chromosomes 1 and 2, but not chromosome 3 (Supplemental Figure S3). Whereas a previous RNA-seq study with these CTD mutants (12) did not appear to uncover broad upregulation of gene expression within the subtelomeric regions, RNA-seq analyses typically remove from consideration sequences that align to repetitive regions such as the subtelomere. Indeed, many of the subtelomeric genes identified as being up-regulated in our study have zero reads associated with them in the RNAseq dataset (Supplemental Table S2). Nevertheless, of the few subtelomeric genes that were preserved in that study, for example, the RecQ type DNA helicase thl2 was found to be similarly upregulated, matching our observation.

Given that the CTD mutations resulted in changes in gene expression within subtelomeric regions that are expected to exist in a heterochromatic state, we assayed the repressive heterochromatin mark H3K9 methylation using chromatin immunoprecipitation and subsequent sequencing (ChiP-seq). The H3K9 methylation levels were generally reduced in the first ∼20–45 kb of chromosomes 1 and 2, but not chromosome 3, often overlapping the regions of increased gene expression in the CTD mutants. However, two regions were identified where the gene expression levels were high and yet the H3K9 methylation levels were also high. These regions, most prominently on the left arm of chromosome 1 and the right arm of chromosome 2, contain the thl1 and thl2 genes that encode RecQ type DNA helicases and are thought to nucleate heterochromatin assembly at telomeres (29,30). Given that expression of thl1 and thl2 is increased despite elevated H3K9 methylation, their expression may be necessary or perhaps even privileged for proper heterochromatin formation at these sites. Alternatively, there may exist subtelomeric repression mechanisms that are dependent on RNAP II CTD status, yet are independent of H3K9me. Supporting this view, the regions of upregulated gene expression identified here seem to extend ∼50 kb further into the chromosome than the zones...
of decreased H3K9 methylation, consistent with the idea that subtelomeric chromatin is distinct from euchromatin (31, 32).

The precise mechanisms by which the RNAPII CTD mutations affect chromatin structure and gene expression remain to be elucidated. Several of the CTD repeat mutations examined here yielded similar yet distinct phenotypes, suggesting that the relevant CTD ‘reader’ protein(s) may recognize more than one CTD residue. While future work will be required to identify the relevant reader(s), it is tempting to speculate that disruption of phosphorylation events on the CTD alters recruitment of chromatin modifying enzymes such as members of the Set family of histone methyltransferases. For example, Set2 associates with the phosphorylated form of the CTD (33), and Set2 protein levels have also been shown to be destabilized in CTD phosphomutants (34). Similarly, recent studies in S. cerevisiae have shown that Set1 and Set5 act together to modulate subtelomeric silencing (35). Whether these activities or components of the repressive machinery itself recognize the CTD in this current context will require a biochemical identification of the proximal recognition factor(s).

SUPPLEMENTARY DATA
Supplementary Data are available at NAR Online.

ACKNOWLEDGEMENTS
We would like to thank members of the Ithaca College Experimental Biochemistry lab course: Ledon Black, Brittany Bunch, Lindsey Johnson, Yuta Naro, Freda Opoku, Huy Truong for their contributions.

FUNDING
Research Corporation for Scientific Advancement Cottrell College Science Award (to M.I.); National Institutes of Health (NIH) [GM098634 to J.A.P., GM52470 to S.S., B.S., GM71801 to H.D.M.]. Funding for open access charge: NIH [GM098634]. Conflict of interest statement. None declared.

REFERENCES


