Dysfunction of Chromatin Assembly Factor 1 Induces Shortening of Telomeres and Loss of 45S rDNA in *Arabidopsis thaliana*  

Iva Mozgová, Petr Mokroš, and Jiří Fajkus  

Division of Functional Genomics and Proteomics, Department of Experimental Biology, Faculty of Science, Masaryk University, CZ-61137 Brno, Czech Republic  

Institute of Biophysics, Academy of Sciences of the Czech Republic, v.v.i., CZ-61265 Brno, Czech Republic  

Chromatin Assembly Factor 1 (CAF1) is a three-subunit H3/H4 histone chaperone responsible for replication-dependent nucleosome assembly. It is composed of three subunits: FASCIATA1 (FAS1), FAS2, and MULTICOPY SUPPRESSOR OF IRA1 (MSI1) (Kaya et al., 2001), which correspond to Chromatin Assembly Complex 1 (CAC1) to CAC3 in budding yeast (*Saccharomyces cerevisiae*). CAF1 is a three-subunit H3/H4 histone chaperone responsible for replication-dependent nucleosome assembly. It is composed of three subunits: FASCIATA1 (FAS1), FAS2, and MULTICOPY SUPPRESSOR OF IRA1 (MSI1) (Kaya et al., 2001), which correspond to Chromatin Assembly Complex 1 (CAC1) to CAC3 in budding yeast (*Saccharomyces cerevisiae*). CAF1 displays structural and biochemical activity conservation across eukaryotes, including yeasts (Kaufman et al., 1997), animals (Tyler et al., 1999, 2001), and plants (Kaya et al., 2001). The large subunit (FAS1/CAC1/p150) binds histones H3/H4 and interacts with DNA polymerase processivity factor, the proliferating cell nuclear antigen (Shibahara and Stillman, 1999). The middle subunit (FAS2/p60/CAC2) is a WD40 repeat protein responsible for protein–protein interactions within CAF1 and further mediates interaction with the Antisilencing function 1 factor stimulating nucleosome assembly by CAF1 and participating in replication-independent nucleosome assembly (Tyler et al., 1999, 2001; Munakata et al., 2000; Sharp et al., 2001; Mello et al., 2002; Tagami et al., 2004), heterochromatin protein 1 (Murzina et al., 1999), methyl binding protein1 (Reese et al., 2003), or the BLM and WRN helicases (Jiao et al., 2004, 2007). The small subunit of CAF1 (MSI1/p48/CAC3) belongs to the MSI-like family of WD40 repeat proteins, which apart from participating in CAF1 take part in a number of complexes involved in chromatin dynamics (Hennig et al., 2005).

CAF1 is required for cell proliferation and early development in animals (Hoek and Stillman, 2003; Ye et al., 2003; Nabatiyan and Krude, 2004; Houlard et al., 2006; Takami et al., 2007) but is not essential for the viability of yeast (Kaufman et al., 1997; Enomoto and Berman, 1998) or *Arabidopsis thaliana* (Kaya et al., 2001) if only FAS1 or FAS2 are disrupted. Due to its involvement in the PRC2-like (Polycomb repressor complex) complexes in Arabidopsis, MSI1 is essential for sporophyte, gametophyte, and early seed development (Hennig et al., 2003, 2005; Kohler et al., 2003). Mutants affecting CAF1 displayed reduced position-dependent gene silencing at telomeres (Enomoto et al., 1997; Kaufman et al., 1997; Monson et al., 1997), centromeres (Dohke et al., 2008), the silent mating type loci (Enomoto and Berman, 1998; Dohke et al., 2008), and rDNA (Smith et al., 1999). Proliferating cell nuclear antigen and CAF1 association has also been linked to DNA repair, in particular nucleotide excision repair (Gaillard et al., 1996; Martini et al., 1998; Moggs et al., 2000; Mello et al., 2002; Polo et al., 2006), and to major mechanisms of double strand break (DSB) repair, such as homologous recombination (HR) and nonhomologous end joining (Lewis et al., 2005; Linger and Tyler, 2005; Nabatiyan et al., 2006; Song et al., 2007).

*Arabidopsis* mutants in CAF1 subunits were originally described as causing stem fascination, abnormal leaf and flower morphology, and organization of apical meristems (Reinholt, 1966; Leyeser and Furner, 1992; Kaya et al., 2001). CAF1 is also involved in the regulation of heterochromatinization and maintenance of
characteristic of Plant Lines

To explore the link between DNA replication, chromatin assembly, and telomere maintenance, we collected different mutant alleles of the genes FAS1 (At1g65470) and FAS2 (At5g64630) generated in different genetic backgrounds. Mutants carried either a point mutation or a T-DNA insertion, causing partial or complete disruption of FAS1 or FAS2 expression (see Supplemental Tables 1 and 2 and Supplemental Figure 1 online). Two different T-DNA insertion alleles named fas1-4 were described concurrently by Exner et al. (2006) (ecotype Columbia [Col]) and Kirik et al. (2006) (ecotype C24); these are referred to as fas1-4 and fas1-4b, respectively. Although all the fas alleles have been morphologically and genotypically described before, we located the truncated T-DNA in fas1-4b to exon 1 rather than exon 6 as reported previously (Kirik et al., 2006) and observed no full-length RT-PCR product in fas1-4b/fas1-4b (see Supplemental Figure 1 online). However, we detected FAS1 transcripts originating from the 3' region relative to the T-DNA insertion site. Since the fas phenotype is partially penetrant in heterozygous plants in this line, there is a possibility this mutation may result in dominant-negative forms of FAS1.

Propagation of the FAS mutants was accompanied by progressive loss of viability and fertility (see Supplemental Figure 2 online), presumably resulting in sterility in further generations.

Mutations in FAS1 or FAS2 Cause Telomere Shortening on All Chromosome Arms and Are Associated with the Formation of Anaphase Bridges

We observed significantly reduced lengths of terminal restriction fragments (TRFs) in fas1-2 (Nossen [No]), fas2-1 (Landsberg erecta [Ler]), and fas2-2 (No) plants; regardless of the original (ecotype-specific) telomere lengths in wild-type plants, which ranged from a median of 3 to 5 kb, the mutant telomere lengths ranged around a median of 1.5 to 2.0 kb (see Supplemental Figure 3 online). To explore the dynamics and possible progressiveness of the telomere shortening, we examined the segregating lines fas1-4b (C24), fas1-4 (Col), and fas2-4 (Col). Homozygous mutant and wild-type plants were obtained from two heterozygous parents in the line fas1-4b and three heterozygous parents in the lines fas1-4 and fas2-4. Homozygous mutants were propagated by selfing, generating homozygous lines. Gradual telomere shortening was observed from generation G2 onwards in mutants fas1-4b/fas1-4b (see Supplemental Figures 3B and 3C online), although this line could not be propagated in larger numbers beyond generation G3 due to radical loss of fertility. We were able to propagate the fas1-4/ fas1-4 and fas2-4/fas2-4 plants for at least five generations. While telomeres of wild-type plants retained median length of 2.7 to 3.0 kb, telomeres in mutants progressively shortened over three to five generations to approximately one-half, yielding telomeres of median length 1.5 to 1.7 kb (Figures 1A and 1B), the shortest being around 700 bp. Progressive shortening is most
remarkable after the transition from the heterozygous parental generation (P) to generation G1 of homozygous mutant plants when ~800 bp of telomeric DNA per chromosome arm is lost. This is followed in later generations by a slower loss of the telomeric tracts (200 to 300 bp per generation) and homogenization of telomere lengths. These results are consistent for plants bearing either FAS1 or FAS2 mutations (Figure 1C). We next used the PCR-based method PETRA (for primer extension telomere repeat amplification) (Heacock et al., 2004) to determine the telomere lengths on separate chromosomal arms with a focus on both arms of chromosomes 2 and 4. In agreement with data from TRFs, the results showed that telomeres on all the chromosome arms studied undergo shortening to a similar extent, regardless of the original wild-type telomere length on that particular arm (see Supplemental Figures 4 and 5 online). Increased formation of anaphase bridges was observed in the later generations of fas mutants (3.7%, n = 1084 in G5 mutant, compared with 0.3%, n = 653 in G5 wild type), indicating inadequate protection of the chromosome termini (Figure 1D).

Shortening of Telomeres in Mutants Is Quickly Reversed by the Presence of a Wild-Type Allele

To understand the nature of the telomere shortening in FAS mutants, we crossed (1) the fas1-4 and fas2-4 mutant plants in generation G4 with their corresponding wild types and (2) the fas1/fas1 with the fas2/fas2 plants in G2 to generate a population of plants heterozygous at both loci. Crossing of fas mutant plants with wild-type plants yields a heterozygous population in the generation F1, but the individuals have from one to three populations of telomeres (clearly separated peaks of similar intensities). The lengths of the separate populations correspond to the telomere lengths of the wild type and mutant parents and/or are intermediate (Figure 2A). In the F2 generation, the length difference between the three populations decreases through elongation of the shortest and the intermediate telomeres. The fas/fas plants in F2 always displayed only a single population of medium length telomeres, indicating shortening of the longest telomeres and possibly lengthening of shortest telomeres in F1. Similarly, when fas1 and fas2 homozygous mutants are reciprocally crossed, the telomeres elongate immediately in F1 of the heterozygous progeny and reach almost wild-type lengths in F2. Importantly, this cross yields only one population of telomeres that slightly elongates in each generation (Figure 2B).

Mutations in FAS1 and FAS2 Induce a Major Progressive Loss of 45S rDNA from Both Loci on Chromosomes 2 and 4, but Other Repeats Are Not Affected

DNA gel dot blot experiments with genomic DNA isolated from three pooled 5-week-old plants revealed a radical loss of the number of 45S rDNA repeats (Figure 3). The copy number reduction is similar in fas1-4 and fas2-4 mutants and amounts to ~10 to 20% of the repeats per generation, leaving in G5 ~20% of the repeats in fas1-4 and 12% in fas2-4 mutants. There were major losses of the 45S rDNA at the transition from parental generation to G1 (~22% in fas1-4/fas1-4 and 40% in fas2-4/fas2-4). Separate analysis of five individual plants in G2 and G5 indicated that the variability in the amount of 45S rDNA is low within a population of mutants (see Supplemental Figure 6 online). Surprisingly, none of the other analyzed tandem or dispersed repeats (180-bp centromeric repeat, 5S rDNA, retrotransposon repeats).

Figure 2. Elongation of Telomeres in the Presence of a Wild-Type Allele.

Telomere lengths and examples of TRF analysis (right in each panel) in two filial generations (F1 and F2) of reciprocal crosses between mutant and wild-type plants in generation G4 (A) or between fas1 and fas2 mutant plants in generation G2 (B). Error bars indicate SD. Progeny of one parental line is shown. Multiple populations of telomeres defined when clearly separated peaks of similar intensities within one sample appeared (examples indicated by arrows). FAS/FAS, wild type; fas/fas, mutant; FAS/fas, heterozygote; P, parental plants.
Athila, or transposon CACTA) diminished in copy number in the fas mutants (Figure 3).

Real-time quantitative PCR (Q-PCR) on leaves of 5-week-old plants confirmed the results for plants of generations G2 and G5. In fas1-4 and fas2-4 mutants, the amount of 45S rDNA decreases to ~40 and 36% in G2 and 15 and 8% in G5 of levels found in wild-type plants. Interestingly, the values are higher in seedlings of the same generation; for fas1-4 and fas2-4 mutant seedling DNA used in Q-PCR, the values were ~54 and 54% in G2 and 28 and 14% in G5 (Figure 4A).

Fluorescence in situ hybridization signals of 5S rDNA and 25S rDNA in metaphase figures prepared from wild-type and mutant plants from the lines fas1-4 and fas2-4 were quantified (n = 103 to 108 wild type and 140 to 141 mutant nuclei). Reduced intensity of the 25S rDNA signal in the mutant compared with wild-type nuclei verified the previous results and further showed that the localization and number of the signals are unchanged. The intensity, localization, or number of 5S rDNA signals or F6N15 signals (positive hybridization control) was similar in the mutants and the wild types. The reduced 25S rDNA signal intensity was observed on both of the 45S rDNA loci on chromosomes 2 and 4 (Figures 5A and 5B). In cells where the nucleoli are clearly visible, the majority of the 25S rDNA signal in the wild-type interphase cells forms a knob in the perinucleolar space with multiple weak signals emanating into the nucleolus, while the 25S rDNA signal in the mutant cells is entirely intranucleolar, resembling the intranucleolar portion of the wild-type signal.

We were interested to see whether the loss of 45S rDNA also occurs in mutants of fas1 and fas2 in different genetic backgrounds. We observed reduced amounts of 45S rDNA repeats in fas1-2 (No), fas2-1 (Ler), and a progressive reduction in G1 to G3 fas1-4b (C24) mutant plants (Figure 4C; see Supplemental Figure 7 online). Only the fas2-2 (No) mutants (Gn) displayed a higher amount of 45S rDNA than the wild type (Figure 4C; see Supplemental Figure 7 online). No systematic difference in the amount of centromeric repeats or 5S rDNA was observed in these plants. Based on these results, we suggest that the same phenomenon occurs regardless of ecotype, indicating a common mechanism and effect of the loss of function of the FAS proteins.

**Contraction of Telomeric or 45S rDNA Repeats Does Not Affect Levels of Their Transcripts**

Since ongoing transcription and the impairment of CAF1 function are expected to cause perturbations in chromatin structure, we performed micrococcal nuclease (MNase) digestion of the nuclei of G4 fas1-4 and fas2-4 wild-type and mutant plants (Figure 6B). Ethidium bromide–stained gels of size-fractionated DNA reveal that the bulk nucleosomes had moderately perturbed periodicity in mutant plants compared with the wild type, and this slight difference was observed when DNA gel blots were hybridized with specific probes. However, the experiment did not reveal any significant difference in the level of perturbation between the sequences that change in copy number (telomere and 18S rDNA) and those that do not (180-bp repeat and 5S rDNA).

We further asked whether the reduced copy numbers of 45S rDNA lead to a change in the overall transcriptional level of the 45S rDNA loci. We also questioned whether the presumed
reduction in telomere silencing (Enomoto et al., 1997; Kaufman et al., 1997; Schonrock et al., 2006) alters the amount of the telomeric repeat-containing RNA, which can negatively regulate telomerase activity and induce replication fork arrest within telomeric DNA (Azzalin et al., 2007; Luke et al., 2008; Schoeftner and Blasco, 2008; Ng et al., 2009). We performed RNA dot hybridization with 18S rDNA and telomeric probes and Q-PCR on RNA isolated from fas1-4 and fas2-4 mutant and wild-type seedlings. In the tested generations G2 to G5 of mutant plants, we did not detect any significant progressive or consistent changes in the level of 18S rDNA transcripts (Figure 4B) or in the abundance of G-rich or the C-rich telomeric sequence transcripts (see Supplemental Figure 8 online).

Neither Telomerase Activity nor the Amount of Extrachromosomal DNA Changes in the FAS Mutants

To find possible mechanism(s) of the selective loss of telomeric and 45S rDNA repeats in the fas mutants, we first analyzed the activity of telomerase in vitro. The telomere repeat amplification protocol (TRAP) assay showed no significant difference in the activity of telomerase between the wild-type and mutant seedlings (Figure 6A). Repetitive sequences are naturally prone to recombination events that are documented by the presence of extrachromosomal DNA (eccDNA) derived from these repeats (Cohen et al., 2008). An overall increased level of recombination has been observed in the fas mutants (Endo et al., 2006; Kirik et al., 2006; Schonrock et al., 2006; Ramirez-Parra and Gutierrez, 2007), and in yeast, the level of recombination increases at the rDNA loci when enhanced transcription from a reduced number of rDNA copies collides with their replication (Takeuchi et al., 2003). Using neutral-neutral two-dimensional (2D) gel electrophoresis, we analyzed the levels of eccDNA originating either

Figure 4. Relative Amount of 45S rDNA in All Studied Plant Lines Estimated by Quantitative PCR.

Amount of repeats in mutants is related to the wild-type plants of corresponding ecotypes where generation of mutant is unknown (Gn) or to segregated wild type of the same generation (G1, G2, and G5). Asterisks indicate significant difference from 1 based on Student’s t test: *P < 0.05; **P < 0.001. Error bars indicate SD.

(A) Lines fas1-4 and fas2-4, seedlings, and 5-week-old plants.
(B) Relative (mutant/wild type) expression of 18S rDNA in generations 2 to 5 of lines fas1-4 and fas2-4.
(C) Lines fas1-2, fas1-4b, fas2-1, and fas2-2, 5-week-old plants.

Figure 5. Fluorescence in Situ Hybridization of fas Mutants.

(A) Comparison of the 5S (red) and 45S (green) loci in representative G5 fas1-4 metaphase and interphase nuclei. FAS/FAS, wild type; fas/fas, mutant.
(B) Quantification of fluorescence intensities of Cy3 (5S rDNA probe) and AF488 (25S rDNA probe) and DEAC (BAC clone F6N15 probe) related to 4',6-diamidino-2-phenylindole in metaphase nuclei. Error bars indicate SD. n(wt) = 103/108, n(+/C0/C0) = 140/141 nuclei for fas1-4 and fas2-4, respectively. Wild-type and mutant plants of generation G5 were used. The wild type was arbitrarily set as 1. All values for mutant samples are significantly different from one based on a Student’s t test: P < 0.001. −/−, Mutant.
from the telomeric or from 45S rDNA loci to find typical by-products of recombination frequently leading to amplification or contraction of these repeats. Although we were able to detect eccDNAs originating from telomeres and 45S rDNA, we did not observe any difference in their amounts between wild-type and mutant plants (Figure 7).

**DISCUSSION**

**CAF1 Dysfunction Leads to Reduction of Telomeric and 45S rDNA Repeats**

We show that mutations in the genes *FAS1* and *FAS2*, encoding two of the three subunits of CAF1 in *Arabidopsis*, cause a progressive reduction of telomeric and 45S rDNA repeats. The results are consistent for both *fas1* and *fas2* mutants, suggesting that the observed phenotype is caused by a dysfunction of CAF1 rather than by a separate involvement of the two subunits in other pathways. The mutations in *FAS1* and *FAS2* are marked by a decrease in median telomere lengths from 3 to 7 kb in the wild type depending on ecotype, to 1.5 to 2 kb in mutants regardless of ecotype (Figure 1; see Supplemental Figure 3 online). The 45S rDNA copy number in *fas1-4* and *fas2-4* wild-type and mutant plants in generation G4. (−/−), Mutant.

from the telomeric or from 45S rDNA loci to find typical by-products of recombination frequently leading to amplification or contraction of these repeats. Although we were able to detect eccDNAs originating from telomeres and 45S rDNA, we did not observe any difference in their amounts between wild-type and mutant plants (Figure 7).

**DISCUSSION**

**CAF1 Dysfunction Leads to Reduction of Telomeric and 45S rDNA Repeats**

We show that mutations in the genes *FAS1* and *FAS2*, encoding two of the three subunits of CAF1 in *Arabidopsis*, cause a progressive reduction of telomeric and 45S rDNA repeats. The results are consistent for both *fas1* and *fas2* mutants, suggesting that the observed phenotype is caused by a dysfunction of CAF1 rather than by a separate involvement of the two subunits in other pathways. The mutations in *FAS1* and *FAS2* are marked by a decrease in median telomere lengths from 3 to 7 kb in the wild type depending on ecotype, to 1.5 to 2 kb in mutants regardless of ecotype (Figure 1; see Supplemental Figure 3 online). The 45S rDNA copy number in *fas1-4* and *fas2-4* (Col) mutants is reduced to 10 to 20% of the wild-type level by the 5th generation of homozygous mutants (Figure 3) implying that 57 to 120 copies of the estimated 570 copies per haploid genome (Pruitt and Meyerowitz, 1986) remain. A similar phenomenon with a variable extent of reduction is observed in different ecotypes of *Arabidopsis*. Apart from telomeres and 45S rDNA, other major repetitive sequences in the *Arabidopsis* genome tested do not display changes in copy numbers. These repeats are as follows: tandemly repeated 5S rDNA and 180-bp centromeric pAL sequences (Round et al., 1997; Heslop-Harrison et al., 1999), major centromeric Ty3/Gypsy-type retrotransposon *Athila* (Pelissier et al., 1995, 1996), and mobile pericentromeric transposon *CACTA1*, which is transcriptionally activated in *fas* mutants (Ono et al., 2006). The propagation of the *fas* mutants is limited by progressive decrease in fertility and viability, but the extent of the phenotypic defects is variable within and between different ecotypes.

Although rDNA and telomeres both represent major tandem repeats, the molecular mechanisms of their loss need not be identical but may reflect the diverse effects of disturbed chromatin assembly in the *fas* mutants on the distinct mechanisms underlying copy number maintenance of these repeats (see below).

**Telomere Shortening and Chromosome-End Deprotection**

Although increased recombination has been described in the *fas* mutants (Endo et al., 2006; Kirik et al., 2006), several facts argue against the recombination-based mechanism of telomere loss, telomere rapid deletion (Lustig, 2003), in the shortening of telomeres. Recombination at telomeres is downregulated by their folding into a compact nucleoprotein structure (Fajkus et al.,...
standard telomerase activity in vitro (Figure 6A). There is faster loss of telomeres on transition from heterozygous parent into G1 (600 to 700 bp) and slower loss (100 to 300 bp) to stabilization in subsequent generations (Figures 1A to 1C). Telomere shortening in later generations may be counteracted by the increased accessibility for telomerase due to shorter telomere lengths that (1) prevent formation of telomerase-repressive t-loop structures and/or (2) enable the more slowly progressing replication machinery to reach telomere ends. Such a scenario could explain the observed shortening of telomeres in yeast CAF1 mutants (Enomoto et al., 1997), whose shorter telomere lengths of ~300 bp may not constitute an obstacle for their full replication.

Reestablishment of permissive conditions for the telomerase activity in heterozygotes could be a possible explanation of the quick reversal of telomere lengths we observed after backcrossing fas/fas with FAS/FAS plants and crossing fas1/fas1 with fas2/ fas2 plants (Figure 2). Telomerase has been shown to preferentially act on shorter telomeres (Hemann et al., 2001; Samper et al., 2001; Shakirov and Shippen, 2004; Teixeira et al., 2004; Chang et al., 2007), and telomere length is specific and stable in each Arabidopsis ecotype (Riha et al., 2001, 2002; Shakirov and Shippen, 2004; Maillet et al., 2006). This may explain the increase in lengths of the shortest and intermediate telomere lengths and the stable lengths of the longest wild-type telomeres in F2 progeny of the mutant × wild-type crosses (Figure 2A). Altogether, the observed telomere dynamics suggest that telomere maintenance rather than telomere protection is compromised in the fas mutants.

The rate of shortening (but not the homogeneous distribution of telomere lengths) and the progressive increase in the severity of the fas phenotype resembles telomere shortening and its consequences induced by mutation in telomerase catalytic subunit TERT (Fitzgerald et al., 1996; Ruckova et al., 2008). Since the severity of the fas phenotype is variable among plants from lines fas1-4 and fas2-4 where the rate of telomere shortening is similar and since telomere shortening in the morphologically severe mutants fas1-4b is mild, the loss of telomeric tract is not the only contributor to the loss of viability in these plants. However, a fragile telomere stability resulting in telomere de-protection in the fas mutants is documented by the presence of anaphase bridges in 3.7% of anaphases in G5 mutants, which in some cases show severe developmental defects and low fertility (<10 seeds collected from one plant). The number of anaphase bridges exceeds the 0.7% observed in the G5 tert mutants where rapid increase of anaphase bridges and an onset of developmental defects occur in later generations (Riha et al., 2001). This difference could be attributed to the fast shortening of telomeres from parental generation to G1 fas mutants, which may speed up the process of telomere shortening below the threshold of 1 kb, described as the critical telomere length at which the chromosomes get susceptible to fusions (Heacock et al., 2007).

**rDNA Loss and Genomic Instability**

rDNA copy number is maintained via recombination induced by frequent formation of DSBs at the replication fork barriers within the intergenic spacer of the yeast 35S rDNA (reviewed in
Kobayashi, 2006; Labib and Hodgson, 2007; Tsang and Carr, 2008). Although the mechanism of rDNA copy number maintenance in plants has not been described so far, the replication fork barriers have been documented in plants (Hernandez et al., 1993; Lopez-Estrano et al., 1999), and the intergenic spacer of the 45S rDNA has been identified as a recombination hot spot (Urawa et al., 2001). Whereas the yeast 5S rDNA is subjected to joint copy number regulation as a part of the 35S rDNA locus (Kobayashi, 2006), the separate localization and possibly different regulation of the 45S and the 5S rDNA loci in Arabidopsis may explain the selective loss of the 45S and not the 5S rDNA in the fas mutants (Figure 3; see Supplemental Figure 7 online). Since dysfunction of CAF1 in plants has been connected to increased numbers of DNA DSBs, increased level of HR, and upregulation of genes involved in HR (Endo et al., 2006; Kirik et al., 2006; Schonrock et al., 2006; Ramirez-Parr and Gutierrez, 2007), it is possible that disruption of a recombination-based maintenance equilibrium may lead to the 45S rDNA loss. However, the bias toward the deterministic loss of the sequences needs to be explained. The fact that we did not observe any increase in the level of eccDNA derived from 45S rDNA loci (Figure 7) may indicate that increased recombination is limited to an early developmental stage (Cohen and Mechali, 2002; Liu et al., 2007). However, since the loss of rDNA in the fas mutants seems continuous (Figure 4), and since the presence of eccDNA was detected in adult plants (Figure 7), it is unlikely that recombination-based losses are restricted to early ontogeny. Alternatively, the sequences may not be lost through eccDNA but as other recombination by-products.

The 45S rDNA loss was observed in all the studied lines of fas mutants with the exception of the line fas2-2, where shorter telomeres (see Supplemental Figure 3 online) but higher amounts of 45S rDNA (Figure 4C; see Supplemental Figure 7 online) were observed in mutants than in the corresponding wild type. Several facts may contribute to this difference: (1) The wild-type and mutant lines are unrelated plants, which may differ in the abundance of rDNA repeats, as was previously reported in other plant species (Rogers and Bendich, 1987a, 1987b). (2) The allele fas2-2 carries a point mutation that causes a frameshift, resulting in a termination codon 98 amino acids downstream of the mutation (Kaya et al., 2001). We have not detected any alternatively spliced transcripts, and the mutation has been confirmed on the level of cDNA. Thus, we may speculate that the translation results in a protein that is partly functional or whose function is altered by its C-terminal part. Alternatively, ribosome slippage may revert the frameshift, generating a partly functional FAS2. Reduction of 45S rDNA copy number is more dramatic in the phenotypically more severe fas2-4 mutants with no detectable transcription of fas2, than in fas1-4 mutants with only reduced expression of fas1. A question arises whether rDNA reduction could account for the variable severity of the fas phenotype. Only a subset (estimated to 10 to 27% in Arabidopsis) of the 45S rRNA genes are transcriptionally active (Grummt and Pikaard, 2003; Pontes et al., 2003). It is plausible that the 10 to 20% of the original rDNA copies maintained by the G5 fas mutants can provide sufficient amounts of rRNA, and this is in agreement with the unchanged amount of 18S rRNA in the mutants (Figure 4B). It is therefore unlikely that inadequate transcription of 45S rDNA could explain the progressive severity of the fas phenotype in the five studied generations. Transcriptionally silent copies of the rDNA have been cytologically identified as the condensed rDNA knobs that may be associated with the nucleoli, while the active copies are seen as multiple partly decondensed intranucleolar signals (Leitch et al., 1992; Pontes et al., 2003; Lawrence and Pikaard, 2004). In G5 fas mutants, we observed the 25S rRNA as decondensed multiple foci inside the nucleoli, which suggests that the majority of the remaining rDNA copies are transcriptionally active (Figure 5). Further loss of rDNA in the next generations of fas mutants can be expected to result in inadequate supply of rRNAs originating from the 45S rDNA loci.

Although most of the rDNA copies are dispensable for normal plant development (Rogers and Bendich, 1987b), low numbers of rDNA repeats have been previously implicated in the phenotype severity and sterility of the Drosophila melanogaster mutant bobbed (Ritossa, 1968), in release of heterochromatin-induced gene silencing (Paredes and Maggert, 2009), in reduced rDNA condensation and cohesion (Kobayashi and Ganley, 2005), and increased sensitivity to DNA damage when transcribed by RNA polymerase I (Ide et al., 2010). These results support a hypothesis that redundant copies of rRNA genes play an essential role in maintaining genome stability (Kobayashi, 2008). Whether the reduced position-dependent gene silencing observed in the CAF1 mutants and the progressive nature of the fas phenotype can be at least partly attributed to the progressive reduction of rDNA copies needs to be further assessed. It is however possible that later generation fas mutants present an extreme state where the few 45S rDNA repeats are extensively transcribed, and this may contribute to genome instability.

Numerous questions have been raised and need to be addressed in future, including: (1) What are the mechanisms of rDNA copy number maintenance in plants? (2) What is/are the mechanism/s responsible for the initiation and progress of the selective copy number reduction? (3) What are the consequences of their loss in the fas mutants. Studies examining the telomere and rDNA dynamics in plants with combined mutations in FAS and other genes regulating telomere and rDNA maintenance or DNA repair are in progress to resolve mechanisms leading to the fas phenotype.

METHODS

Plant Material and Genotyping of Mutants

All studies were performed in the following plant lines: fas1-2 (No) (Kaya et al., 2001), fas1-4 (Col) (NASC: N828822, SAIL_662_D10, described in Exner et al., 2006), fas1-4b (C24) (Kirik et al., 2006), fas2-1 (Ler) (Leyser and Furner, 1992), fas2-2 (No) (Kaya et al., 2001), fas2-4 (Col) (NASC: N533228, SALK_033228 (H) (AE), described in Exner et al., 2006) (see also Supplemental Table 1 and Supplemental Figure 1 online). Lines fas1-1, fas2-1, and fas2-2 had been propagated as homozygous mutants for an unknown number of generations and were grown for two more generations in parallel to wild-type plants of ecotypes of the appropriate genetic background. Lines fas1-1, fas1-4, fas1-4b, and fas2-4 were obtained as progeny of heterozygous parents and served to segregate wild-type and mutant lines. In fas1-4 and fas2-4 lines, three FAS/fas parents gave 9 × FAS/FAS and 15 × fas/fas in three G1 lines, two lines served to give 12 × FAS/FAS and 18 × fas/fas in G2, and one line of 6 × FAS/FAS and 9 × fas/fas was
propagated into G3 to G5. In line FAS1-4b, two FAS/fas parents gave \(9 \times FAS/FAS\) and \(10 \times fas/fas\) in G1, \(15 \times FAS/FAS\) and \(13 \times fas/fas\) in G2, and \(9 \times FAS/FAS\) and \(7 \times fas/fas\) in G3. To obtain the crosses between \(fas/fas\) and wild types, three independent lines were crossed and propagated into F1, and one line (total of seven plants) was propagated into F2 (26 plants); in the case of \(fas1/fas1 \times fas2/fas2\), one line of plants was observed (total of three plants in F1 and 29 plants in F2). Seeds were surface sterilized and pregrown on half-strength Murashige and Skoog plates for 2 weeks when the plants were put into soil and grown under the conditions of 16 h light, 21°C and 8 h dark, 19°C. 100 \(\mu\)mol/m²s⁻¹. For genotyping, DNA was isolated using the IRRI method (Collard et al., 2007), and 1 \(\mu\)L of this DNA was used in a PCR reaction using DyNAzyme II DNA polymerase (Finnzymes). Combinations of primers used, their sequences, and sizes of PCR products can be found in Supplemental Tables 2 and 3 online. Genotyping results were confirmed in the high-purity DNA isolated according to Dellaporta et al. (1983) from the selected plants.

**DNA Isolation**

DNA was isolated from 2-week-old seedlings or from rosette leaves of 5-week-old plants according to Dellaporta et al. (1983). Quality of DNA was checked, and concentration was determined from 0.8% (w/v) agarose gel stained with ethidium bromide using Gene Ruler 1 kb DNA Ladder (Fermentas) as standard and Multi Gauge software (Fujifilm).

**RNA Isolation and Reverse Transcription**

RNA was isolated from 100 mg of 2-week-old seedlings using the RNeasy plant mini kit (Qiagen) according to the manufacturer’s instructions. RNA was extensively treated with DNase I (TURBO DNA-free; Applied Biosystems/Ambion), concentration was determined using NanoPhotometer (Finnzymes), with random hexamers (Finnzymes) according to the manufacturer’s instructions.

**Q-PCR**

Q-PCR was performed in the same way on cDNA, DNA from 2-week-old seedlings, and DNA from 5-week-old plants using RotorGene3000 (Corbett Life Science). FastStart SYBR Green Master (RoX; Roche) was used with the combination of primers UB10f and UB10r for ubiquitin (single 186-bp product) and 18SF and 18Sr for 18S rDNA (single 226-bp product) (see Supplemental Table 3 online). The same cycling conditions were applied to both primer combinations: denaturation 95°C/60 s and 8°C/15 s and 60°C/60 s. The SYBR Green I fluorescence was monitored after each extension step at 60°C. The amount of 18S rDNA repeats or transcripts was normalized to ubiquitin. All samples were analyzed in triplicates in three repeated experiments.

**Telomere Length Analysis: TRFs**

Five hundred nanograms of genomic DNA isolated from leaves of individual 5-week-old plants were digested overnight by Tru11 (Msel) (Fermentas) and separated in 0.8% (w/v) agarose gel at 1.5 V/cm, 16 h, at room temperature. Agarose gels with TRFs were washed in 0.25 M HCl for 15 min and 0.4 M NaOH for 30 min and blotted in 0.4 M NaOH onto Hybond XL membrane (GE Healthcare). TRFs were hybridized overnight at 55°C with telomere-specific probe TR4C (CCCTAAA)₄, end-labeled with [γ-³²P]ATP using T4 polynucleotide kinase (NEB), and visualized using the FLA7000 imager (Fujifilm). Evaluation of product sizes was done using software Multi Gauge with Gene Ruler 1 kb DNA Ladder (Fermentas) as standard. Only samples loaded on the same gel were mutually compared. TRFs were evaluated as the median of the population of telomere lengths, and two or more populations within one plant were distinguished only if the maxima of the individual populations formed clearly separated peaks.

**Dot Blot Hybridization**

Probes for hybridization were PCR-generated using Phusion High-Fidelity DNA Polymerase (NEB) from genomic DNA with the following sets of primers (for sequences of all primers, see Supplemental Table 3 online): 180-bp centromeric repeat: pALF + pALR (Davison et al., 2007) (single copy 136 bp), 18S rDNA: 18SF + 18Sr (226 bp), 5S rDNA: 5SLF + 5SLr (single-copy 436 bp), Athila: ORF1f + ORF1r (Davison et al., 2007) (126 bp), and CACTA: SP15 + SP40 (Kato et al., 2003) (713 bp). The products were inserted into vector pCRII-TOPO (Invitrogen) and sequenced. The probe used as a single-copy gene reference (locus At1g49950 coding for putative telomere binding protein TRB1) was amplified from genomic DNA using primers TRB1F and TRB1r, inserted into pDONR2Zeo (Invitrogen), and sequenced. Final TRB1 probe was amplified from the vector using primers TRB1F and TRB1r, generating an 1891-bp product. Probes for hybridization were amplified from the vector using insert-specific primers and radioactively labeled using the DecaLabel DNA labeling kit (Fermentas). Telomeric probe TR4C was labeled as for TRF analysis.

DNA was isolated from 1.2 g of leaves mixed from three 5-week-old plants, 0.4 g each. The variability of the amounts of repetitive sequences was tested on five plants prior to mixing the three plants into one sample. All the experiments were done in three independent biological replicates (plants grown at different times). Genomic DNA (250, 100, 40, and 16 ng) was diluted into 200 \(\mu\)L of 0.4 M NaOH and 10 mM EDTA, and samples were denatured at 95°C for 10 min and cooled on ice. They were spotted onto Hybond XL membrane (GE Healthcare) and subjected to hybridization with sequence-specific probes. All membranes were done in triplicates and hybridized first with the TRB1 DNA loading reference probe, washed and hybridized with two other probes in the order of increasing hybridization signal of the particular probes (i.e., pAL < 18S rDNA, TR4C < CACTA, and Athila < 5S). All probes were hybridized in 0.25 M Na-phosphate, pH 7.5, 7% SDS, and 0.016 M EDTA overnight at 65°C and washed with 0.2× SSC + 0.1% SDS, except for At TR4C, which was hybridized at a lower stringency (55°C) and washed with 2× SSC + 0.1% SDS. The signal was evaluated using Multi Gauge absolute signal strength calculated from linear regression lines and normalized to the signal of TRB1. The obtained value of wild-type DNA in generation G1 was arbitrarily set as 1, and all the other values were related to this G1 wild-type sample.

**Fluorescence in Situ Hybridization**

Mitotic chromosomes were prepared from flower bud pistils of wild-type and mutant plants derived from the same heterozygous parent, which were simultaneously grown under the conditions described above, as described by Mokros et al. (2006). The whole protocol was performed in parallel on mutant and wild-type samples, and the same aliquot of the hybridization probes was used for both types of samples. For visualization of the 45S rDNA loci, an internal 2478-bp (EcoRI) fragment of the 25S rRNA gene was used (Kiss et al., 1989). The clone pCT4.2, corresponding to a 500-bp 5S RNA repeat (M65137), was used for localization of 5S rDNA loci. The probes were directly labeled by AF488-dUTP and Cy3-dUTP, respectively. DEAC-labeled BAC clone F6N15 (GenBank accession number AF069299) was used as an internal hybridization control. The fluorescence in situ hybridization procedures were performed according to Mandakova and Lysak (2008). All images were acquired using the same parameters, and integrated fluorescence intensities were quantified by ISIS imaging software (MetaSystems) in nuclei found in the same cell.
cycle phase (metaphase or interphase). Fluorescence intensities of AF488, Cy3, and DEAC were normalized to 4',6-diamidino-2-phenylindole.

MNase Digestion

Two grams of leaves from three 5-week-old plants were used for isolation of nuclei according to Espinas and Carballo (1993), and isolated nuclei were washed and resuspended in 50 mM TrisCl, pH 8, 125 mM saccharose, 3 mM CaCl₂, 5 mM MgCl₂, 10 mM MeSH, 250 μM spermidine, and 100 μM PMSF, divided into four aliquots, and digested with 90 units of MNase (Takara Bio) for 3, 10, or 30 min. After proteinase K treatment and ethanol precipitation, the isolated DNA was separated in 2% (w/v) NuSieve 3:1 agarose (Lonza) gel at 1 V/cm overnight at room temperature. Fluorescence intensities of 18S rDNA or telomeric probe were detected after DNA gel blot hybridization as described.

TRAP

Protein extracts from 2-week-old seedlings were prepared according to Fitzgerald et al. (1996). These extracts were subjected to the TRAP assay as described by Fajkus et al. (1998). TS21 was used as the substrate primer for extension by telomerase and TEL-PR as the reverse primer (see Supplemental Table 3 online) in the subsequent PCR.

2D Agarose Gel Electrophoresis

To probe for eccDNA, 2D agarose gel electrophoresis was conducted according to modified protocols of Cohen and Lavi (1996), Zellinger et al. (2007), and Navratilova et al. (2008). DNA was isolated from 5-week-old plants as for dot blot hybridization. Five micrograms of genomic DNA with the addition of 5.7- and 11.8-kb plasmids, 5 ng each, were digested with a total of 30 units of Plasmid-Safe ATP-Dependent DNase (Epicenter Biotechnologies) overnight. DNA was precipitated and separated in 0.4% TBE with 0.3 g/mL ethidium bromide at 4 V/cm, 6 h, at room temperature. The gel was then blotted and hybridized with telomeric TR4C, 18S rDNA, and plasmid probes as described.

Statistical Analysis

All data were statistically analyzed using two-tailed unpaired Student’s t test with $\sigma_A = \sigma_B$.

Accession Numbers

Sequence data from this article can be found in the Arabidopsis Genome Initiative data libraries under the following locus identifiers: FAS1 (At1g65470) and FAS2 (At5g64630).

Supplemental Data

The following materials are available in the online version of this article.

Supplemental Figure 1. Characterization of Plant Material.

Supplemental Figure 2. Examples of the fas Phenotype.

Supplemental Figure 3. Telomere Length Maintenance in Lines fas1-2, fas1-4b, fas2-1, and fas2-2.

Supplemental Figure 4. Lengths of Telomeres on Individual Chromosome Arms in fas1-4.

Supplemental Figure 5. Lengths of Telomeres on Individual Chromosome Arms in fas2-4.

Supplemental Figure 6. Relative Amount of 45S rDNA in Individual Plants from Generations 2 and 5 of Lines fas1-4 and fas2-4.

Supplemental Figure 7. Relative Amount of Repetitive Sequences in fas1-2, fas1-4b, fas2-1, and fas2-2 Estimated by Dot Blot Hybridization.

Supplemental Figure 8. Relative Expression of Telomeric Repeats in fas1-4 and fas2-4.

Supplemental Table 1. Overview of FAS Mutants Used.

Supplemental Table 2. Genotyping fas Mutants.

Supplemental Table 3. Oligonucleotides Used.

ACKNOWLEDGMENTS

We thank Ales Pecinka and Ortrun Mittelsten Scheid for providing seeds of fas1-4 and fas2-4, Masaki Endo and Seiichi Toki for seeds of fas1-2, fas2-1, fas2-2, and corresponding wild-type seeds, and Bernd Reiss for seeds of fas1-4b. We also thank Miloslava Fojtova, Tomas Pavlik, and David Potesil for helpful consultations, Andrew R. Leitch for critical reading of the manuscript, and Jana Kapustova for technical assistance. We are further grateful to the reviewers of this manuscript for their valuable suggestions and comments. This research was funded by the Czech Ministry of Education (MSM0021622415 and LC06004), Czech Science Foundation (204/08/H054), the Academy of Sciences of the Czech Republic (AV0Z50040507 and AV0Z50040702), and the Masaryk University Rector’s Programme (MUNI/g/0104/2009).

Received April 28, 2010; revised July 13, 2010; accepted July 21, 2010; published August 10, 2010.

REFERENCES

Abe, M., Kuroshita, H., Umeda, M., Roh, J., and Nagato, Y. (2008). The rice flattened shoot meristem, encoding CAF-1 p150 subunit, is required for meristem maintenance by regulating the cell-cycle period. Dev. Biol. 319: 384–393.

Azzalin, C.M., Reichenbach, P., Khoriauli, L., Giuliani, E., and Lingner, J. (2007). Telomeric repeat containing RNA and RNA surveillance factors at mammalian chromosome ends. Science 318: 798–801.

Chang, M., Arneric, M., and Lingner, J. (2007). Telomerase repeat addition processivity is increased at critically short telomeres in a Tel1-dependent manner in Saccharomyces cerevisiae. Genes Dev. 21: 2485–2494.

Chen, Z., Tan, J.L., Ingouff, M., Sundaresan, V., and Berger, F. (2006). Chromatin assembly factor 1 regulates the cell cycle but not cell fate during male gametogenesis in Arabidopsis thaliana. Development 133: 65–73.

Cohen, S., and Lavi, S. (1996). Induction of circles of heterogeneous sizes in carcinogen-treated cells: Two-dimensional gel analysis of circular DNA molecules. Mol. Cell. Biol. 16: 2002–2014.

Cohen, S., and Mechali, M. (2002). Formation of extrachromosomal circles from telomeric DNA in Xenopus laevis. EMBO Rep. 3: 1168–1174.

Cohen, S., Houben, A., and Segal, D. (2008). Extrachromosomal circular DNA derived from tandemly repeated genomic sequences in plants. Plant J. 53: 1027–1034.
Collard, B.C.Y., Das, A., Virk, P.S., and Mackill, D.J. (2007). Evaluation of "quick and dirty" DNA extraction methods for marker-assisted selection in rice (Oryza sativa L.). Plant Breed. 126: 47–50.

Davison, J., Tyagi, A., and Comai, L. (2007). Large-scale polymorphism of heterochromatic repeats in the DNA of Arabidopsis thaliana. BMC Plant Biol. 7: 44.

Dellaporta, S.L., Wood, J., and Hicks, J.B. (1983). A plant DNA minipreparation: Version II. Plant Mol. Biol. Rep. 1: 19–21.

Denchi, E.L. (1983). A plant DNA minipreparation: Version II. Plant Mol. Biol. Rep. 1: 19–21.

Enomoto, S., McCune-Zierath, P.D., Gerami-Nejad, M., Sanders, M.A., and Berman, J. (1998). Chromatin assembly factor I, essential and couples chromatin assembly to DNA replication in vivo. Proc. Natl. Acad. Sci. USA 100: 12183–12188.

Endo, M., Ishikawa, Y., Osakabe, K., Nakayama, S., Kaya, H., Araki, T., Shibahara, K., Abe, K., Ichikawa, H., Valentine, L., Hohn, B., and Toki, S. (2006). Increased frequency of homologous recombination and T-DNA integration in Arabidopsis CAF-1 mutants. EMBO J. 25: 5579–5590.

Exner, V., Taranto, P., Schonrock, N., Gruissem, W., and Hennig, L. (2006). Chromatin assembly factor CAF-1 is required for cellular differentiation during plant development. Development 133: 4163–4172.

Fan, X., and Price, C.M. (1997). Coordinate regulation of G and C strand length during new telomere synthesis. Mol. Biol. Cell 8: 2145–2155.

Fitzgerald, M.S., McKnight, T.D., and Shippen, D.E. (1996). Characterization and developmental patterns of telomerase expression in plants. Proc. Natl. Acad. Sci. USA 93: 14422–14427.

Gaillard, P.H., Martini, E.M., Kaufman, P.D., Stillman, B., Moustacchi, E., and Almouzni, G. (1998). Chromatin assembly coupled to DNA repair: A new role for chromatin assembly factor I. Cell 88: 887–896.

Greider, C.W., and Blackburn, E.H. (1989). Identification of a specific telomere terminal transferase activity in Tetrahymena extracts. Cell 51: 405–413.

Grummt, I., and Pikaard, C.S. (2003). Epigenetic silencing of RNA polymerase I transcription. Nat. Rev. Mol. Cell Biol. 4: 641–649.

Heacock, M., Spangler, E., Riha, K., Puizina, J., and Shippen, D.E. (2004). Molecular analysis of telomere fusions in Arabidopsis: Multiple pathways for chromosome end-joining. EMBO J. 23: 2304–2313.

Hennig, L., Taranto, P., Palser, M., Schonrock, N., and Gruissem, W. (2003). Arabidopsis MSI1 is required for epigenetic maintenance of reproductive development. Development 130: 2555–2565.

Hennig, L., Bouveret, R., and Gruissem, W. (2005). MSI1-like proteins: An escort service for chromatin assembly and remodeling complexes. Trends Cell Biol. 15: 295–302.

Houard, M., Berivet, S., Probst, A.V., Quivy, J.P., Hery, P., Almouzni, G., and Gerard, M. (2006). CAF-1 is essential for heterochromatin organization in pluripotent embryonic cells. PLoS Genet. 2: e181.

Jiao, R., Zachariadis, E., Pedrazzini, T., Kaelin, W., Li, J.L., Egli, D., Hickson, I.D., and Stagljar, I. (2004). Physical and functional interaction between the Bloom’s syndrome gene product and the largest subunit of chromatin assembly factor 1. Mol. Cell. Biol. 24: 4710–4719.

Kato, M., Miura, A., Bender, J., Jacobsen, S.E., and Hakuta, T. (2003). Role of CG and non-CG methylation in immobilization of transposons in Arabidopsis. Curr. Biol. 13: 421–426.

Kobayashi, T., and Komai, H. (2001). Chromatin assembly factor CAF-1 following DNA damage. Oncogene 20: 3811–3822.

Kobayashi, T., Shibahara, K.I., Taoka, K.I., Iwabuchi, M., Stillman, B., and Greider, C.W. (2007). Telomerase-mediated telomere terminal transferase activity in Tetrahymena extracts. Cell 126: 280–291.

Kouzarides, T., Grewal, S.I., and Jalkanen, M. (2007). Telomerase-mediated telomere terminal transferase activity in Tetrahymena extracts. Cell 126: 280–291.

Kraft, D.J., and Almouzni, G. (1998). Chromatin assembly coupled to DNA repair: A new role for chromatin assembly factor I. Cell 88: 887–896.

Kraft, D.J., and Almouzni, G. (1998). Chromatin assembly coupled to DNA repair: A new role for chromatin assembly factor I. Cell 88: 887–896.

Kraft, D.J., and Almouzni, G. (1998). Chromatin assembly coupled to DNA repair: A new role for chromatin assembly factor I. Cell 88: 887–896.

Kraft, D.J., and Almouzni, G. (1998). Chromatin assembly coupled to DNA repair: A new role for chromatin assembly factor I. Cell 88: 887–896.

Kraft, D.J., and Almouzni, G. (1998). Chromatin assembly coupled to DNA repair: A new role for chromatin assembly factor I. Cell 88: 887–896.

Kraft, D.J., and Almouzni, G. (1998). Chromatin assembly coupled to DNA repair: A new role for chromatin assembly factor I. Cell 88: 887–896.

Kraft, D.J., and Almouzni, G. (1998). Chromatin assembly coupled to DNA repair: A new role for chromatin assembly factor I. Cell 88: 887–896.

Kraft, D.J., and Almouzni, G. (1998). Chromatin assembly coupled to DNA repair: A new role for chromatin assembly factor I. Cell 88: 887–896.

Kraft, D.J., and Almouzni, G. (1998). Chromatin assembly coupled to DNA repair: A new role for chromatin assembly factor I. Cell 88: 887–896.
Living with genome instability: plant responses to telomere dysfunction. Science 291: 1797–1800.

Riha, K., Watson, J.M., Parkey, J., and Shippen, D.E. (2002). Telomere length deregulation and enhanced sensitivity to genotoxic stress in Arabidopsis mutants deficient in Ku70. EMBO J. 21: 2819–2826.

Ritossa, F.M. (1968). Unstable redundancy of genes for ribosomal RNA. Proc. Natl. Acad. Sci. USA 60: 509–516.

Rogers, S.O., and Bendich, A.J. (1987a). Heritability and variability in ribosomal RNA genes of Vicia faba. Genetics 117: 285–295.

Rogers, S.O., and Bendich, A.J. (1987b). Ribosomal RNA genes in aging in Terc−/− mice with short telomeres. EMBO Rep. 2: 800–807.

Shakirov, E.V., and Shippen, D.E. (2004). Length regulation and dynamics of individual telomere tracts in wild-type Arabidopsis. Plant Cell 16: 1959–1967.

Sharp, J.A., Fouts, E.T., Krawitz, D.C., and Kaufman, P.D. (2001). Yeast histone deposition protein Asf1p requires Hir proteins and PCNA for heterochromatic silencing. Curr. Biol. 11: 463–473.

Shibahara, K., and Stillman, B. (1999). Replication-dependent marking of DNA by PCNA facilitates CAF-1-mediated inheritance of chromatin. Cell 96: 575–585.

Schoeftner, S., and Blasco, M.A. (2008). Developmentally regulated transcription of mammalian telomeres by DNA-dependent RNA polymerase II. Nat. Cell Biol. 10: 228–236.

Schoeftner, S., and Blasco, M.A. (2009). A ‘higher order’ of telomere regulation: Telomere heterochromatin and telomeric RNAs. EMBO J. 28: 2323–2336.

Schonrock, N., Exner, V., Probst, A., Gruissem, W., and Hennig, L. (2006). Functional genomic analysis of CAF-1 mutants in Arabidopsis thaliana. J. Biol. Chem. 281: 9560–9568.

Smith, J.S., Caputo, E., and Boeke, J.D. (1999). A genetic screen for ribosomal DNA silencing defects identifies multiple DNA replication and chromatin-modulating factors. Mol. Cell. Biol. 19: 3184–3197.

Smith, S., and Stillman, B. (1989). Purification and characterization of CAF-I, a human cell factor required for chromatin assembly during DNA replication in vitro. Cell 58: 15–25.

Smith, S., and Stillman, B. (1991). Stepwise assembly of chromatin during DNA replication in vitro. EMBO J. 10: 971–980.

Song, Y., He, F., Xie, G., Guo, X., Xu, Y., Chen, Y., Liang, X., Stagljar, I., Egli, D., Ma, J., and Jiao, R. (2007). CAF-1 is essential for Drosophila development and involved in the maintenance of epigenetic memory. Dev. Biol. 311: 213–222.

Tagami, H., Ray-Gallet, D., Almouzni, G., and Nakatani, Y. (2004). Histone H3.1 and H3.3 complexes mediate nucleosome assembly pathways dependent or independent of DNA synthesis. Cell 116: 51–61.

Takami, Y., Ono, T., Fukagawa, T., Shibahara, K., and Nakayama, T. (2007). Essential role of chromatin assembly factor-1-mediated rapid nucleosome assembly for DNA replication and cell division in vertebrate cells. Mol. Biol. Cell 18: 129–141.

Takeuchi, Y., Horiiuchi, T., and Kobayashi, T. (2003). Transcription-dependent recombination and the role of fork collision in yeast rDNA. Genes Dev. 17: 1497–1506.

Teixeira, M.T., Armeric, M., Sperisen, P., and Linger, J. (2004). Telomere length homeostasis is achieved via a switch between telomerase-extendible and -nonextendible states. Cell 117: 323–335.

Tsang, E., and Carr, A.M. (2008). Replication fork arrest, recombination and the maintenance of ribosomal DNA stability. DNA Repair (Amst.) 7: 1613–1623.

Tyler, J.K., Adams, C.R., Chen, S.R., Kobayashi, R., Kamakaka, R.T., and Kadonaga, J.T. (1999). The RCAF complex mediates chromatin assembly during DNA replication and repair. Nature 402: 555–560.

Tyler, J.K., Collins, K.A., Prasad-Sinha, J., Amiott, E., Bulger, M., Harte, P.J., Kobayashi, R., and Kadonaga, J.T. (2001). Interaction between the Drosophila CAF-1 and ASF1 chromatin assembly factors. Mol. Cell. Biol. 21: 6574–6584.

Urawa, H., Hidaka, M., Ishiguro, S., Okada, K., and Horiiuchi, T. (2001). Enhanced homologous recombination caused by the non-transcribed spacer of the rDNA in Arabidopsis. Mol. Genet. Genomics 266: 546–555.

Verreault, A., Kaufman, P.D., Kobayashi, R., and Stillman, B. (1996). Nucleosome assembly by a complex of CAF-1 and acetylated histones H3/H4. Cell 87: 95–104.

Vrbsky, J., Akimcheva, S., Watson, J.M., Turner, T.L., Daxinger, L., Vyskot, B., Aufsatz, W., and Riha, K. (2010). siRNA-mediated methylation of Arabidopsis telomeres. PLoS Genet. 6: e1000986.

Watson, J.M., and Shippen, D.E. (2007). Telomere rapid deletion regulates telomere length in Arabidopsis thaliana. Mol. Cell. Biol. 27: 1706–1715.

Ye, X., Franco, A.A., Santos, H., Nelson, D.M., Kaufman, P.D., and Adams, P.D. (2003). Defective S phase chromatin assembly causes DNA damage, activation of the S phase checkpoint, and S phase arrest. Mol. Cell 11: 341–351.

Zellinger, B., Akimcheva, S., Puizina, J., Schirato, M., and Riha, K. (2007). Ku suppresses formation of telomeric circles and alternative telomere lengthening in Arabidopsis. Mol. Cell 27: 163–169.
