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Citation for published version:

Digital Object Identifier (DOI):
10.1101/gad.332536.119

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Publisher's PDF, also known as Version of record

Published In:
Genes & Development

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Hap2–Ino80-facilitated transcription promotes de novo establishment of CENP-A chromatin

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Centromeres are maintained epigenetically by the presence of CENP-A, an evolutionarily conserved histone H3 variant, which directs kinetochore assembly and hence centromere function. To identify factors that promote assembly of CENP-A chromatin, we affinity-selected solubilized fission yeast CENP-ACnp1 chromatin. All subunits of the Ino80 complex were enriched, including the auxiliary subunit Hap2. Chromatin association of Hap2 is Ies4-dependent. In addition to a role in maintenance of CENP-ACnp1 chromatin integrity at endogenous centromeres, Hap2 is required for de novo assembly of CENP-ACnp1 chromatin on naïve centromere DNA and promotes H3 turnover on centromere regions and other loci prone to CENP-ACnp1 deposition. Prior to CENP-ACnp1 chromatin assembly, Hap2 facilitates transcription from centromere DNA. These analyses suggest that Hap2–Ino80 destabilizes H3 nucleosomes on centromere DNA through transcription-coupled histone H3 turnover, driving the replacement of resident H3 nucleosomes with CENP-ACnp1 nucleosomes. These inherent properties define centromere DNA by directing a program that mediates CENP-ACnp1 assembly on appropriate sequences.

[Keywords: CENP-A; centromere; chromatin; chromosome segregation; epigenetic; fission yeast; histone; kinetochore; remodeling; transcription]

Supplemental material is available for this article.

Received September 9, 2019; revised version accepted December 11, 2019.

The accurate delivery of all chromosomes to both resulting nuclei during mitotic cell division is required for eukaryotic cell viability and to prevent aneuploidy, a hallmark of cancer [Kops et al. 2005]. The centromere region of chromosomes mediates their attachment to spindle microtubules for normal mitotic chromosome segregation [Fukagawa and Earnshaw 2014]. In many organisms, centromeres are assembled on repetitive elements such as α-satellite repeats, minor satellite repeats, cen180/CentC/CentO repeats, and retroelements at human, mouse, plant, and Drosophila centromeres, respectively [Kipling et al. 1991; Grady et al. 1992; Cheng et al. 2002; Chang et al. 2019]. Although such centromere repeats lack sequence similarity, in many cases their introduction as naked DNA into cells triggers de novo kinetochore assembly [Baum et al. 1994; Okada et al. 2007].

The underlying conserved feature at eukaryotic centromeres is the assembly of nucleosomes containing the histone H3 variant CENP-A (also generally known as cenH3, and specifically as CID in Drosophila, Cse4 in Saccharomyces cerevisiae, and Cnp1 in Schizosaccharomyces pombe) in place of canonical H3 to direct kinetochore assembly on such repetitive elements. Moreover, it is known that following deletion of an endogenous centromere, CENP-A incorporation and neocentromeres can arise at novel noncentromeric DNA locations [Ishii et al. 2008; Ketel et al. 2009; Shang et al. 2013]. CENP-A chromatin has also been shown to be sufficient to trigger kinetochore assembly [Barnhart et al. 2011; Mendiburo et al. 2011; Hori et al. 2013; Chen et al. 2014]. Thus, CENP-A deposition and not the primary sequence of centromere DNA determines the position of centromere formation. However, centromere DNA itself may harbor properties that favor CENP-A and kinetochore assembly [Baum et al. 1994; Fachinetti et al. 2015; Logsdon et al. 2019].

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Three fission yeast species possess complex regional centromeres in which CENP-A_{Cnp1} and kinetochores are assembled over a nonrepetitive central domain of ~10 kb in *S. pombe*, *S. octosporus*, and *S. cryophilus* (Tong et al. 2019). Although flanking gene order is preserved, the central domain sequence is not conserved among these species. Despite this lack of similarity, central domain DNA from *S. octosporus* and *S. cryophilus*, as well as *S. pombe*, can direct de novo CENP-A_{Cnp1} and kinetochore assembly in *S. pombe* (Folco et al. 2008; Catania et al. 2015; Tong et al. 2019). This suggests that these nonhomologous centromere DNAs possess innate features that program events that preferentially trigger the assembly of CENP-A_{Cnp1} in place of H3 nucleosomes.

During replication, parental CENP-A has been shown to distribute equally to nucleosomes on duplicated DNA of both sister centromeres, thus halving the amount of CENP-A at each centromere [Jansen et al. 2007; Schuh et al. 2007]. Replenishment by deposition of newly synthesized CENP-A is temporally separated from DNA replication-coupled H3 chromatin assembly. The timing of new CENP-A deposition differs in various species; mitotic/late telophase/early G1 in human and *Drosophila* (Schuh et al. 2007; Erhardt et al. 2008; Mellone et al. 2011), S phase in *S. cerevisiae* (Pearson et al. 2004), and G2 in plants and *S. pombe* [Lermontova et al. 2006; Shukla et al. 2018].

Several studies have reported the association of RNA polymerase II (RNAPII) with and/or transcription from CENP-A-associated DNA so that noncoding transcription has become an apparent integral feature of centromeres (Duda et al. 2017). RNAPII has been detected at human artificial chromosome [HAC] [Bergmann et al. 2011], human metaphase [Chan et al. 2012], *Drosophila* [Bobkov et al. 2018], and *S. cerevisiae* [Ohkuni and Kitagawa 2011] centromeres, and also the central domains of fission yeast centromeres [Choi et al. 2011; Catania et al. 2015]. Disruption of centromere transcription appears to hinder CENP-A loading and/or maintenance [Nakano et al. 2008; Bergmann et al. 2011; Chen et al. 2015; McNulty et al. 2017; Ling and Yuen 2019]. Moreover, increased centromere transcription results in the rapid loss of CENP-A and centromere function [Hill and Bloom 1987; Bergmann et al. 2012]. The central CENP-A_{Cnp1} domains from *S. pombe* centromeres contain numerous RNAPII transcriptional start sites and promoters [Choi et al. 2011; Catania et al. 2015]. In addition, ectopically located central domain DNA, which lacks CENP-A_{Cnp1} chromatin, exhibits high rates of histone H3 turnover [Shukla et al. 2018]. Such observations suggest that transcription-coupled chromatin remodeling events might drive the eviction of H3 and its replacement with CENP-A_{Cnp1}. Consistent with this view, the accumulation of elongating RNAPII on ectopic centromere DNA during G2 coincides with the eviction of H3 and deposition of new CENP-A [Shukla et al. 2018]. However, it remains to be determined which transcription-associated chromatin remodeling factors provoke the replacement of H3 with CENP-A on naïve centromere DNA.

Various ATP-dependent chromatin remodeling complexes provide access to the underlying DNA of chromatin-coated templates. Their activities enable transcription by disassembling nucleosomes, sliding nucleosomes, or replacing nucleosomal histone subunits with transcription-promoting variants [Clapier and Cairns 2009]. The remodeling and spacing factor [RSF] interacts with CENP-A chromatin in mid-G1, its depletion reduces CENP-A levels at centromeres [Perpelescu et al. 2009], and tethering of RSF1 to centromere repeats promotes histone turnover/exchange resulting in both H3.3 and CENP-A deposition [Ohzeki et al. 2016]. In *S. pombe*, Hrp1 (ortholog of chromo-helicase DNA-binding protein 1 [CHD1]) is enriched at centromeres and is required to maintain normal CENP-A_{Cnp1} levels at centromeres [Walfridsson et al. 2005; Choi et al. 2011]. Loss of the histone chaperone facilitates chromatin transcription [FACT] results in promiscuous CENP-A_{Cnp1} assembly at noncentromeric locations A_{Cnp1} (Choi et al. 2012), suggesting that CENP-A_{Cnp1} may be titrated away from centromeres by loss of such factors. Moreover, inducible ectopic centromeres in *Drosophila* requires FACT-mediated RNAPII-dependent transcription of underlying DNA, indicating a necessity for transcription during CENP-A assembly [Chen et al. 2015].

Ino80 is a Snf2 family ATPase evolutionarily conserved from yeast to humans that participates in transcription, DNA replication, and DNA repair [Conaway and Conaway 2009]. The Ino80 complex [Ino80C] can slide nucleosomes in an ATP-dependent manner [Chen et al. 2011] and can space multiple nucleosomes on longer DNA fragments [Udugama et al. 2011]. Ino80C may also remove H2A.Z–H2B dimers from nucleosomes, replacing them with H2A–H2B dimers [Papamichos-Chrakakis et al. 2011; Brahma et al. 2017]. H2A.Z is enriched in +1 nucleosomes downstream from promoters of many active genes, and loss of Ino80 function affects transcription [Hogan et al. 2010; Marques et al. 2010; Xue et al. 2015]. Individual Ino80C subunits make up three modules that associate with the main Ino80 ATPase subunit [Supplemental Table S1; Chen et al. 2011]. *S. pombe* Ino80 has been shown to influence the maintenance of CENP-A_{Cnp1} chromatin at centromeres [Choi et al. 2017]. However, it is not known whether Ino80C influences centromere DNA transcription or the establishment of CENP-A chromatin on naïve centromere DNA and, thus, centromere identity.

Here we used affinity selection of CENP-A_{Cnp1} chromatin and mass spectrometry to identify proteins enriched in CENP-A_{Cnp1} chromatin that may promote CENP-A_{Cnp1} assembly. We identify Hap2 [SPCC16C4.20] as an auxiliary subunit of Ino80C that is required for the conversion of H3 chromatin to CENP-A_{Cnp1} chromatin on naïve centromere DNA. We show that loss of Hap2 function reduces transcription and histone H3 turnover on centromere DNA. Our findings indicate that Hap2–Ino80 is required to promote transcription-associated chromatin remodelling events that drive H3 nucleosome eviction and the assembly of CENP-A_{Cnp1} nucleosomes in their place.
Results

**Hap2 is an Ino80C subunit that is enriched in CENP-A<sup>Cnp1</sup> chromatin**

To identify proteins involved in the assembly of CENP-A<sup>Cnp1</sup> chromatin, GFP-tagged CENP-A<sup>Cnp1</sup> chromatin was affinity-purified from micrococcal nuclease (MNase)-solubilized chromatin extracts (Fig. 1A). Quantitative PCR (qPCR) analysis of the resulting enriched native chromatin revealed significant enrichment of centromeric DNA from the single-copy central CENP-A<sup>Cnp1</sup> domain of cen2 (cc2) compared with the 18 copies of flanking outer repeat (dg) sequences (Supplemental Fig. S1A). In addition, SDS-PAGE analysis showed core histones to be prevalent in this affinity-selected GFP-CENP-A<sup>Cnp1</sup> material (Fig. 1B; Supplemental Fig. S1B). Label-free quantitative mass spectrometry detected strong enrichment of all known subunits of both the inner and outer kinetochore complexes [Fig. 1C; Supplemental Tables S2, S3].

As our procedure also showed association of the chaperones Scm3 (HJURP) and Sim3 (NASP) that mediate CENP-A<sup>Cnp1</sup> deposition we reasoned that other enriched, but non-centromere-specific, proteins might be involved in the incorporation of CENP-A<sup>Cnp1</sup> into centromeric chromatin.

It was notable that all subunits of the Ino80 chromatin remodeling complex (Ino80C) were enriched in our affinity-selected GFP-CENP-A<sup>Cnp1</sup> preparations [Fig. 1C]. Also enriched in these samples was the low-molecular-weight α-helical Hap2 protein. Hap2 has previously been reported to associate with Ino80C but no characterization has been performed [Hogan et al. 2010]. To confirm association of Hap2 with Ino80C, Hap2 was C-terminally tagged with GFP at its endogenous chromosomal locus (Hap2-GFP) [Supplemental Fig. S2A]. Affinity selection of Hap2-GFP followed by proteomic analysis revealed that all subunits of Ino80C, but not subunits of other remodeling complexes, are enriched with Hap2-GFP [Fig. 1D, Supplemental Table S4]. IP-western analysis confirmed that Hap2-GFP associates with immunoprecipitated HA-tagged Ino80 (Ino80-HA) and vice-versa, independently of DNA/chromatin association [Supplemental Fig. S1C, D]. Furthermore, affinity selection of Ino80-HA enriched all known Ino80C subunits along with Hap2 [Supplemental Fig. S1E; Supplemental Table S5]. We conclude that Hap2 is a noncanonical subunit of the fission yeast Ino80 complex and that all Ino80C subunits are enriched in CENP-A<sup>Cnp1</sup> chromatin.

**Hap2 association with central domain DNA assembled in CENP-A<sup>Cnp1</sup> chromatin or H3 chromatin is Ies4-dependent**

Microscopic analysis showed that Hap2-GFP localizes to the nucleus [Fig. 2A]. Quantitative chromatin immunoprecipitation (qChIP) assays revealed that Hap2-GFP...
Figure 2. Hap2 associates with endogenous and ectopic central core chromatin and Ies4 dependent, Hap2 and Arp5 chromosomal distributions are coincident. [A] Immunolocalization of Hap2-GFP in cells. Representative images of wild-type and Hap2-GFP cells stained with anti-CENP-A-Cnp1 (red), anti-GFP (green), and DAPI (blue). Scale bar, 5 µm. [B] qChIP for Hap2-GFP at four locations within endogenous centromeres (cc1/3, cc2-a, cc2-b, and cc2-c), outer repeat heterochromatin [dg], and noncentromere locus [act1†]. Error bars indicate mean ± SD (n = 3). [C, top] Diagram indicating strain with endogenous cen2-cc2 replaced with cen1 central domain DNA [cc1] at the noncentromeric ura4 locus [ura4-cc2] on Chr III. [Bottom] qChIP for Hap2-GFP at three locations within ectopic centromal domain H3 chromatin [cc2-a, cc2-b, and cc2-c], endogenous centromeres [cc1/3], outer repeat heterochromatin [dg], and noncentromere locus [act1†]. Error bars indicate mean ± SD (n = 3). [D] Comparison of Hap2-GFP association with central domain sequence assembled in CENP-A-Cnp1 chromatin or H3 chromatin [data from B and C]. Error bars indicate mean ± SD (n = 3). Significance of the differences observed between cells containing endogenous centromeres and ectopic central domain DNA was evaluated using Student’s t-test. (†) P < 0.005; (**) P < 0.0005; (***P < 0.0005; n.s.) not significant. (E) qChIP for Hap2-GFP at three locations within ectopic centromal domain H3 chromatin [cc2-a, cc2-b, and cc2-c], endogenous centromeres [cc1/3], outer repeat heterochromatin [dg] and noncentromere locus [act1†] in untagged, wild-type, and ies4Δ cells. (F) Genome-wide coincidence of Hap2-GFP and Arp5-3HA peaks (~60%). Gradient shows enrichment of Hap2 [green] and Arp5 [blue].

associates with most chromatin regions analyzed including the central CENP-A-Cnp1 domain of centromeres (cc2), the flanking pericentromeric outer repeats [dg] and on the highly expressed act1† gene (Fig. 2B). When 8.5 kb of cen2 central domain DNA [cen2-cc2] is inserted at the ura4 locus on a chromosome arm [ura4:cc2], it is assembled in H3 instead of CENP-A-Cnp1 chromatin (Choi et al. 2012; Shukla et al. 2018). Replacement of 6.5 kb of endogenous cen2-cc2 DNA with 5.5 kb of cen1 central domain DNA [cc2Δ:cc1] allows analysis across the resulting unique ectopic copy of cen2 central domain DNA [ura4:cc2] in the absence CENP-A-Cnp1 and kinetochore proteins (Fig. 2C, top). qChIP analysis revealed that Hap2-GFP associates with this ectopic cc2 central domain chromatin [Fig. 2C, bottom]. A noticeably higher level of Hap2-GFP was consistently detected across ectopic ura4:cc2 central domain DNA assembled in H3 chromatin relative to the same DNA sequence at the native cen2 central domain assembled in CENP-A-Cnp1 chromatin [Fig. 2D]. Loss of Hap2 does not affect the association of Ino80-HA with these regions [Supplemental Fig. S2B], while Hap2 chromatin association is lost in the absence of Ies4 but remains unaffected in iec1Δ, ies2Δ and arp5Δ cells [Fig. 2E, Supplemental Fig. S2C,D]. In budding yeast, different subunits of Ino80 have been shown to have broad interactions around NFRs and +1 nucleosomes [Yen et al. 2013]. As Hap2 is a subunit of Ino80C, we examined genome-wide localization of Hap2 and Arp5. High coincidence was observed for Hap2 and Arp5 peaks (Fig. 2F). We conclude that the Ino80C subunit Hap2 is a nuclear protein that associates with noncentromeric loci and is preferentially recruited to centromeric central domain chromatin when assembled in H3 rather than CENP-A-Cnp1 chromatin. Hap2 chromatin association is dependent on the Ino80C subunit Ies4, and Hap2 colocalizes genome-wide with the Arp5 canonical Ino80C subunit.

Hap2 is required to maintain CENP-A-Cnp1 chromatin across endogenous centromeres

Cells lacking Hap2 exhibit an elevated frequency of lagging chromosomes during mitosis, indicating that loss of
Hap2 may affect centromere function [Fig. 3A]. Defective centromere function can result from reduced pericentric heterochromatin formation on dg/db outer repeats or CENP-A<sub>Chnp1</sub> chromatin/kinetochore assembly and these can be sensitively detected by the use of silent ura4<sup>+</sup> reporter genes inserted within outer repeat heterochromatin or central CENP-A<sub>Chnp1</sub> domain chromatin [Allshire et al. 1994, 1995; Partridge et al. 2000]. No alleviation of heterochromatin-mediated silencing at ot1r1: ura4<sup>+</sup> was detected in hap2Δ cells relative to wild type as indicated by similar poor growth on selective plates lacking uracil [−URA] and good growth on counter-selective 5-FOA plates [Fig. 3B; Supplemental Fig. S3A]. Consistent with this observation, no significant change was detected in the levels of the heterochromatin H3K9me2 mark or dg transcripts produced by the underlying outer repeats in hap2Δ relative to wild-type cells [Fig. 3C,D].

Central CENP-A<sub>Chnp1</sub> domain chromatin is also transcriptionally repressive [Allshire et al. 1994, 1995]. Defects in CENP-A<sub>Chnp1</sub> chromatin assembly alleviates this transcriptional silencing [Partridge et al. 2000; Pidoux et al. 2003]. To test whether loss of Hap2 affects CENP-A<sub>Chnp1</sub>-mediated silencing we examined silencing of ura4<sup>+</sup> embedded in central CENP-A<sub>Chnp1</sub> chromatin at cen1 (cc1:ura4<sup>+</sup>). Reduced silencing in hap2Δ cells, indicated by reduced growth on counter-selective FOA plates, suggested a defect in CENP-A<sub>Chnp1</sub> chromatin integrity [Fig. 3E; Supplemental Fig. S3B]. qChIP analysis detected significantly lower levels of CENP-A<sub>Chnp1</sub> and a reciprocal increase in H3 levels across the central domain of centromeres in hap2Δ relative to wild-type cells [Fig. 3F,G], consistent with the silencing defect. Importantly, loss of Hap2 does not affect the total cellular levels of GFP-CENP-A<sub>Chnp1</sub> or the expression of genes encoding proteins that are known to regulate CENP-A<sub>Chnp1</sub> loading at centromeres [Supplemental Fig. S3C,D]. We conclude that loss of Hap2 specifically affects silencing through loss of CENP-A<sub>Chnp1</sub> and gain of H3 within the central domain of centromeres, thus Hap2 is required to maintain CENP-A<sub>Chnp1</sub> chromatin integrity at endogenous centromeres.

Hap2 is required for the de novo establishment of CENP-A<sub>Chnp1</sub> chromatin

Many factors are known to assist CENP-A maintenance but little is known about the factors required for the de novo establishment of CENP-A chromatin. De novo establishment of functional centromeres can occur following the introduction of naked centromere DNA into cells [Catania et al. 2015]. We first examined whether Hap2 and other subunits of Ino80C are required for the de novo establishment of centromeres on the pHcc2 mini-chromosome [Fig. 4A]. hap2Δ cells exhibited a complete failure to establish functional centromeres, similar to clr4Δ cells that lack heterochromatin, while ies2Δ displayed increased establishment, ices1Δ and ies4Δ were less competent in establishing functional centromeres on pHcc2 [Fig. 4B; Supplemental Fig. S4A]. In S. pombe,
Figure 4. Hap2 is required for the de novo establishment of CENP-A<sup>Cnp1</sup> chromatin. (A) Schematic representation of pHcc2 minichromosome K′/dg repeat adjacent to central domain 2 DNA. Position of the primer pair at the edge of K′/dg repeat and within central domain 2 DNA are indicated. (B) Transformants containing pHcc2 minichromosome plasmids were replica-plated to low adenine nonselective plate. Representative plate showing colony color and centromere establishment frequency in wild type (n = 515), hap2Δ (n = 390), and strains lacking heterochromatin clr4Δ (n = 870). (C,D) qChIP for CENP-A<sup>Cnp1</sup> and histone H3 at plasmid-borne central domain 2 DNA [cc2-a] on pHcc2 minichromosome. Error bars indicate mean ± SD (n = 3). (E) qChIP for H3K9me2 demonstrated that loss of Hap2 did not affect the establishment of heterochromatin on the arm of a chromosome, such as the clr4Δ/mini and K′-arm and plasmid-borne central domain 2 DNA [cc2-a] on pHcc2 minichromosome. Error bars indicate mean ± SD (n = 3). (F) H3K9me2 on pHcc2 minichromosome. Error bars indicate mean ± SD (n = 3). (E,F) Transformants containing pHcc2 minichromosome plasmids were replica-plated to low adenine nonselective plate. Representative plate showing colony color and centromere establishment frequency in wild type (n = 515), hap2Δ (n = 390), and strains lacking heterochromatin clr4Δ (n = 870). (C,D) qChIP for CENP-A<sup>Cnp1</sup> and histone H3 at plasmid-borne central domain 2 DNA [cc2-a] on pHcc2 minichromosome. Error bars indicate mean ± SD (n = 3). Significance of the differences observed between wild type and hap2Δ was evaluated using Student’s t-test in C–F. (*) P < 0.05; (**) P < 0.005; (n.s.) not significant.

de novo CENP-A<sup>Cnp1</sup> chromatin establishment on circular plasmid-based minichromosomes requires a block of heterochromatin in close proximity to central domain DNA [Folco et al. 2008; Kagansky et al. 2009]. Loss of centromere establishment could result from a failure to establish CENP-A<sup>Cnp1</sup> chromatin, and/or adjacent heterochromatin, on the minichromosome. To distinguish between these possibilities, CENP-A<sup>Cnp1</sup> levels on the plasmid-borne central domain cc2 DNA were analysed. All strains used have 6 kb of cen2 central domain DNA replaced with 5.5 kb of cen1 central domain DNA at endogenous centromeres [cc2A:cc1] so that the plasmid-borne cc2 is the only copy of this element. qChIP revealed that CENP-A<sup>Cnp1</sup> was not assembled over cc2 carried by pHcc2 in hap2Δ cells [Fig. 4C]. Reciprocally, a high level of H3 was detected across cc2 of pHcc2 in the absence of CENP-A<sup>Cnp1</sup> assembly in hap2Δ cells [Fig. 4D]. qChIP for H3K9me2 demonstrated that loss of Hap2 did not affect the establishment of heterochromatin on the plasmid-borne K′/dg repeat [Fig. 4E]. Interestingly, high levels of H3K9me2 were detected within the central domain of the pHcc2 minichromosome in hap2Δ but not wild-type cells [Fig. 4E]. This suggests that in the absence of CENP-A<sup>Cnp1</sup> chromatin establishment in hap2Δ cells heterochromatin may spread from the outer K′/dg repeat into the plasmid-borne central cc2 domain. To test whether Hap2 is required for the de novo establishment of CENP-A<sup>Cnp1</sup> chromatin independently from the requirement for adjacent heterochromatin, the plasmid pcc2 which carries 8.5 kb of cen2 central domain DNA, but no heterochromatin forming outer repeat sequences, was transformed into cells expressing additional GFP-CENP-A<sup>Cnp1</sup>, which allows CENP-A<sup>Cnp1</sup> chromatin assembly [Fig. 4F, top, Catania et al. 2015]. In contrast to wild type, hap2Δ cells did not assemble high levels of CENP-A<sup>Cnp1</sup> over the central domain of the pcc2 minichromosome [Fig. 4F, bottom]. This effect was not due to altered CENP-A<sup>Cnp1</sup> protein levels in hap2Δ compared with wild-type cells [Supplemental Fig. S4B]. We conclude that Hap2 is critical for the de novo establishment of CENP-A<sup>Cnp1</sup> chromatin on naïve central domain centromere DNA.

Hap2 promotes histone turnover in genomic regions prone to CENP-A<sup>Cnp1</sup> assembly

Central domain DNA inserted at a noncentromeric location on the arm of a chromosome, such as the ura4 locus on chromosome 3 [ura4:cc2], remains assembled in H3 nucleosomes and exhibits a high rate of histone H3 turnover [Shukla et al. 2018]. The inherent instability of H3 nucleosomes assembled on this ectopic ura4:cc2 centromere DNA has been proposed to aid the incorporation of CENP-A<sup>Cnp1</sup> when available [Shukla et al. 2018]. In S. cerevisiae, Ino80 associates with promoter-associated nucleosome-depleted regions and transcription start sites (TSS) where it mediates the turnover of +1 nucleosomes [Yen et al. 2013]. The requirement for Hap2 in de novo CENP-A<sup>Cnp1</sup> assembly on central domain DNA may result from defective H3 nucleosome turnover on these centromeric sequences when assembled in H3 chromatin alone. We therefore used recombination-induced tag exchange (RITE) [Verziel et al. 2010; Shukla et al. 2018] to measure replication-independent H3 turnover in G2-arrested wild-type and hap2Δ cells on ectopic ura4:cc2, heterochromatic repeats, and highly transcribed genes. This H3.2-HA→T7 tag swap was induced in cdc25-22/G2-arrested cells and the incorporation of new histone
H3.2-T7 was monitored (Fig. 5A). Importantly, the H3.2-HA → T7 tag swap efficiency was unaffected by hap2Δ relative to wild-type cells (Supplemental Fig. S5A). Compared with wild-type cells, a significant decrease in the level of H3 turnover was evident on ectopic ura4:cc2 centromere DNA in hap2Δ cells (Fig. 5B). Similarly, H3 turnover within endogenous cen1-cc1 assembled in CENP-ACnp1 chromatin was also reduced in hap2Δ cells. In contrast, H3 turnover remained unchanged within heterochromatic outer repeats [dg] and over highly transcribed genes [act1+ and spd1+].

Ino80 facilitates CENP-A chromatin establishment
transcribed genes (act1+ and spd1+). Ino80 may mediate nucleosome turnover through eviction of H2A.Z (Papamichos-Chronakis et al. 2011). However, the levels of H2A.ZPh1 associated with endogenous cc1 and ectopic ura4:cc2 were unaffected by loss of Hap2 [Supplemental Fig. S5B]. We conclude that Hap2 is required to ensure H3 nucleosome instability on centromeric sequences by mediating a high frequency of H3 turnover, which may consequently allow the incorporation of CENP-A\(^{\text{Cnp1}}\) in place of H3.

Overexpression of CENP-A\(^{\text{Cnp1}}\) results in low levels of promiscuous CENP-A\(^{\text{Cnp1}}\) incorporation at noncentromeric locations (Choi et al. 2012; Castillo et al. 2013). Fusion yeast CENP-A\(^{\text{Cnp1}}\) expression is known to increase prior to that of canonical histones in advance of replication. Consequently, even without overexpression, in early S phase this natural excess of CENP-A\(^{\text{Cnp1}}\) results in low levels of newly synthesized CENP-A\(^{\text{Cnp1}}\) being incorporated across many gene bodies (Shukla et al. 2018). ChIP-Nexus (a modified exo-ChIP-seq protocol) (He et al. 2015) analysis allowed detection of noncentromeric genomic regions where islands of CENP-ACnp1 are reactivated during S phase this natural excess of CENP-ACnp1 results in low levels of RNA-Pol II bound to centromeric sequences by mediating a high frequency of H3 turnover, which may consequently allow the incorporation of CENP-A\(^{\text{Cnp1}}\) in place of H3.

Hap2 facilitates transcription of central domain chromatin

The central CENP-A\(^{\text{Cnp1}}\) domain of S. pombe centromeres is transcribed from many TSS and the resulting RNAs are short-lived (Choi et al. 2011; Sadeghi et al. 2014; Catania et al. 2015). Transcription can provide the opportunity for histone exchange/remodeling of resident nucleosomes (Venkatesh and Workman 2015). It is therefore feasible that transcription-coupled processes also promote the exchange of H3 for CENP-A\(^{\text{Cnp1}}\) in chromatin assembled on centromere DNA. Relatively high levels of RNAPII are detected on centromidal DNA when assembled in H3 chromatins at ectopic ura4:cc2 or on the pcc2 minichromosome, yet only low levels of RNAPII are detectable within endogenous centromeric domain CENP-A\(^{\text{Cnp1}}\) chromatin (Catania et al. 2015; Shukla et al. 2018). Since CENP-A\(^{\text{Cnp1}}\) is primarily deposited prior to that of canonical histones in advance of replication, even without overexpression, in early S phase this natural excess of CENP-ACnp1 results in low levels of RNAPII bound to centromeric sequences by mediating a high frequency of H3 turnover, which may consequently allow the incorporation of CENP-A\(^{\text{Cnp1}}\) in place of H3.

![Figure 6](genesdev.cshlp.org). Figure 6. Transcription from centromeric DNA is reduced in the absence of Hap2. (A) cdc25-22 synchronized cell populations were used to assess levels of RNAPII\(^{\text{SSS}}\) and central core transcripts during G2 in B and C. The separation index for wild type and hap2\(^{\Delta}\) was measured and cells were collected in G2 (T-140). (B) qChIP for initiating RNAPII\(^{\text{SSS}}\) and elongating RNAPII\(^{\text{SSS}}\) levels across ura4:cc2. RNAPII\(^{\text{SSS}}\) levels were significantly lower across this ectopic central domain DNA in hap2\(^{\Delta}\) compared with wild-type cells, but no obvious difference was detected within the CENP-A\(^{\text{Cnp1}}\) chromatin regions of endogenous centromeres. (Fig. 6B). These data suggest that Hap2 promotes efficient transcriptional initiation from central domain DNA that is assembled in H3 chromatins (ura4:cc2). In contrast, the levels of total and elongating RNAPII\(^{\text{SSS}}\) associated with ectopic central domain DNA remained unchanged in hap2\(^{\Delta}\) relative to wild-

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Student's *t*-test was used to determine statistical significance. The differences observed between wild type and hap2\(^{\Delta}\) were evaluated using Student's *t*-test in B–D. **P < 0.05, ***P < 0.005. [n.s.] not significant.
type cells (Supplemental Fig. S6A,B). Consistent with reduced transcriptional initiation, lower levels of central domain transcripts were produced from ectopic ura4::cc2 in hap2Δ cells [Fig. 6C]. Transcript levels from outer repeats and act1 were unaffected. Thus, Hap2 is required for efficient transcriptional initiation and transcription production from ectopic central domain DNA assembled in H3 chromatin. The fact that no decrease in elongating RNAPII S2P was detected across this ectopic central domain in hap2Δ cells suggests that RNAPII remains associated with the central domain template for longer when Hap2 is absent.

Regions upstream of TSS within the central domain of cen2 exhibit promoter activity (Catania et al. 2015). To determine whether Hap2 affects the transcription from these central domain promoters, the production of β-galactosidase was assessed when 200-bp promoter-containing cc2 fragments were placed upstream of lacZ [Fig. 6D, inset]. Three central domain promoters exhibited significantly lower promoter activity in hap2Δ compared with wild-type cells, whereas the control nmt81 promoter was unaffected [Fig. 6D; Supplemental Fig. S6C,D]. We conclude that Hap2 is required for efficient transcription from central domain promoters and that this facilitates transcription-coupled histone exchange, thereby providing an opportunity for replacement of H3 with CENP-A chromatin to establish CENP-A^Cnp1 chromatin domains and assemble functional kinetochores.

Discussion

The mechanisms that contribute to the maintenance, and especially the establishment, of CENP-A chromatin remain poorly understood. To gain insight into how CENP-A chromatin is established on naive centromere DNA, we applied proteomics to identify proteins associated with fission yeast CENP-A^Cnp1 chromatin. In addition to kinetochore proteins, all Ino80C subunits, including the small auxiliary subunit, Hap2, were found to be significantly enriched in solubilized CENP-A^Cnp1 chromatin. Hap2 and the Arp5 Ino80C subunit exhibit similar chromosomal distributions and Hap2 chromatin association depends on the ies4 Ino80C subunit. Hap2 was found to promote CENP-A^Cnp1 chromatin integrity at centromeres and to be required for the de novo establishment of CENP-A^Cnp1 chromatin on introduced naive centromere DNA. The requirement for Hap2 in ensuring high histone H3 turnover on endogenous centromere DNA, ectopically located centromere DNA, and noncentromeric CENP-A^Cnp1 islands indicates that Hap2–Ino80C drives H3 nucleosome turnover at these locations. The loss of CENP-A^Cnp1 incorporation from NCIS islands in the absence of Hap2 underscores the role for Hap2–Ino80C-mediated H3 turnover in stimulating CENP-A^Cnp1 incorporation. Strikingly, Hap2 is required for efficient transcription specifically from central domain promoters. We propose a mechanism in which Hap2–Ino80C drives the inherent instability of H3 nucleosomes on centromeric DNA via transcription-coupled nucleosome turnover, providing the opportunity for incorporation of CENP-A^Cnp1 in place of histone H3, when CENP-A^Cnp1 is available (Fig. 7).

Studies in a variety of species have shown that Ino80C influences transcription (Cai et al. 2007; Klopf et al. 2009; Hogan et al. 2010). The noncanonical human Yin Yang 1 (YY1) transcription factor is known to associate with Ino80 and facilitate both transcriptional activation and repression (Yao et al. 2001; Cai et al. 2007). It is also known that Ino80 suppresses antisense and other noncoding transcription (Alcid and Tsukiyama 2014; Marquardt et al. 2014). The noncoding transcription of centromeric DNA by RNAPII has been implicated in CENP-A deposition in several systems (Chueh et al. 2009; Chen et al. 2012; Rošić et al. 2014; Grenfell et al. 2016; McNulty et al. 2017). However, both reduced and increased transcription of centromere DNA appears to be incompatible with CENP-A chromatin integrity and centromere function (Hill and Bloom 1987; Nakano et al. 2008; Ohtani and Kitagawa 2011; Bergmann et al. 2012). Such observations suggest that an appropriate level and type of programmed transcription may be required to promote CENP-A assembly on centromere DNA.

Each fission yeast centromere contains a central domain of ~10 kb assembled in CENP-A^Cnp1 rather than H3 nucleosomes. Multiple transcriptional start sites are detected on both strands when central domain is assembled in H3, rather than CENP-A^Cnp1, chromatin at an ectopic locus (Choi et al. 2011; Catania et al. 2015), indicating that these regions are pervasively transcribed. Distinct Ino80C modules undertake particular tasks such as nucleosome binding, sliding, and ATPase activity (Chen et al. 2011). The specific impact of Hap2 on Ino80C activity and how this is altered by loss of other subunits such as ies4 remains to be determined. However, a major activity of Ino80C is to slide nucleosomes relative to sizable lengths of flanking unoccupied DNA (Udugama et al. 2011). Thus, the generation of nucleosome free regions that facilitate RNAPII recruitment, and consequently transcription, are an intrinsic facet of Ino80C function. Consequently, the loss of Hap2–Ino80C is expected to occlude central domain promoters with nucleosomes and result in reduced transcriptional initiation.
Since RNAPII recruitment to central domain chromatin during G2 phase of the cell cycle is coincident with H3 eviction and CENP-A^Cnp1 incorporation (Shukla et al. 2018), it is likely that these events are somehow coupled. The conserved heptad repeat composing the C-terminal domain (CTD) of RNAPII undergoes S5 phosphorylation (S5P) at promoters upon transcription initiation and S2 phosphorylation (S2P) in coding regions during transcriptional elongation (Komarnitsky et al. 2000). RNAPII stalls when it encounters obstacles such as DNA damage or natural barriers [Poli et al. 2017]. Despite relatively high levels of RNAPII being detected on H3-assembled ectopic central domain, meagre levels of transcripts are produced, consistent with transcriptional stalling [Choi et al. 2011; Catania et al. 2015]. Analyses in S. cerevisiae show that Ino80 is required to release stalled RNAPII from chromatin and enable its proteosomal degradation [Laton et al. 2015]. Previously, we showed that mutants {\texttt{ubp3Δ, tf3Δ}} expected to increase the levels of stalled RNAPIIS2P on central domain chromatin, promote CENP-A incorporation [Catania et al. 2015]. Interestingly, cells lacking Hap2 display lower initiating RNAPIIIS5P over ectopic H3-assembled central domain chromatin in G2 but the levels of total RNAPII and elongating RNAPII-S2P are unaltered [Fig. 6B, Supplementary Fig. S6A,B]. This indicates that, although lower levels of initiation and transcription take place within ectopic central domain chromatin in the absence of Hap2, elongating RNAPII is retained across the domain. We interpret these observations to indicate that Hap2–Ino80C is required to release elongating RNAPII that becomes trapped or stalled in central domain chromatin. We suggest that resident H3 nucleosomes are evicted by Hap2–Ino80C as part of the process involved in removing this stalled RNAPII. Thus, centromere DNA may be programmed to be pervasively transcribed and stall RNAPII over a relatively large 10-kb region in order to recruit Hap2–Ino80C and trigger H3 turnover throughout this extensive domain, thereby providing the opportunity for CENP-A incorporation. Stalling may result from collisions between converging RNAPII complexes or other obstacles such as the replication origin recognition complex (ORC) which is bound to the many AT-rich tracts present within central domain regions [Hayashi et al. 2007]. Alternatively, elongating RNAPII on central domain DNA may be somehow earmarked for removal using cues analogous to those that allow Ino80 to suppresses antisense and cryptic unstable transcripts [Alcid and Tsukiyama 2014]. Thus, pervasive transcription across an extensive region such as the central domain may itself provoke Ino80C recruitment.

Histone turnover rates are generally higher for nucleosomes close to promoters [Dion et al. 2007]. The +1 nucleosomes exhibit high levels of turnover and Ino80C has been reported to mediate the exchange of H2A.Z for canonical H2A in such nucleosomes [Papamichos-Chronakis et al. 2011; Watanabe et al. 2013; Yen et al. 2013]. However, H2A.Z turnover on transcribed genes has been shown to be not reliant on Ino80 activity [Tramantano et al. 2016]. Moreover, Ino80 is also known to reduce transcription from some promoters, independently of its role in removing H2A.Z [Barbaric et al. 2007]. The fact that no difference in the levels of H2A.Z^Pht1 was detected across the ectopic central domain in hap2Δ cells relative to wild-type [Supplemental Fig. S5B] suggests that Hap2–Ino80C does not mediate H2A.Z^Pht1 eviction from central domain chromatin and that it must affect some other aspect of centromere promoter function, perhaps through its known nucleosome sliding activity. Thus, Ino80C may be required to slide nucleosomes away from central domain promoters so that they are efficiently transcribed and the resulting transcriptional properties of this domain mediate H3 nucleosome turnover.

Previously, we showed that CENP-A^Cnp1 competes with histone H3 for incorporation into centromeric chromatin and CENP-A^Cnp1 incorporation is promiscuous, replacing H3 when the opportunity arises [Castillo et al. 2007; Choi et al. 2011, 2012]. Thus, high histone H3 nucleosome turnover, or low nucleosome occupancy, appears to be an underlying property of many sequences that are prone to CENP-A^Cnp1 assembly in fission yeast. As transcription appears to be widespread at centromeres in other organisms, high turnover of resident H3 nucleosomes, stimulated by Ino80C, may be a conserved attribute of centromeric DNA that stimulates CENP-A deposition.

Materials and methods

Additional methods are described in the Supplemental Material, including lists of strains [Supplemental Table S6], plasmids [Supplemental Table S7], and primers [Supplemental Table S8] used in this study.

Affinity purification mass spectrometry analysis

Native coimmunoprecipitated samples were analyzed on an Orbitrap Fusion Lumos Tribrid mass spectrometer and on a Q Exactive [both from Thermo Fisher Scientific] both coupled online to an Ultimate 3000 RSLCnano system [Dionex, Thermo Fisher Scientific]. For details of the separation, mass spectrometer parameters, and data analysis, see the Supplemental Material and Supplemental Tables S3–S5. The MS proteomics data have been deposited to the ProteomeXchange Consortium via the Proteome Identifications [PRIDE] [Vizcaíno et al. 2016] partner repository with the data set identifier PXD016602.

Establishment assays

Cells transformed with minichromosomes were plated on PMG-uracil-adenine plates and incubated for 5–10 d at 32°C until medium-sized colonies had grown. Colonies were replica-plated to PMG low-adenine (10 µg/mL) plates to determine the frequency of establishment of centromere function. These indicator plates allow minichromosome loss (red colony) or retention (white/pale pink colony) to be determined. In the absence of centromere establishment, minichromosomes behave as episomes that are rapidly lost. Minichromosomes occasionally integrate giving a false-positive white phenotype. To assess the frequency of such integration events and to confirm establishment of centromere segregation function, colonies giving the white/pale-pink phenotype upon replica plating were restreaked to single colonies on
low-adenine plates. Sectored colonies are indicative of segregation function with low levels of minichromosome loss, whereas pure white colonies are indicative of integration into endogenous chromosomes and the establishment frequency was adjusted accordingly.

**LacZ assays**

LacZ assays were performed as described [Guarente 1983]. Plasmids containing LacZ with upstream nmt81 promoter, 200-bp sequences from centromere 2 or no promoter were used as described [Catania et al. 2015]. Plasmids were transformed into wild-type and hap2Δ strains and grown on minimal medium.

**ChIP-seq and ChIP-nexus**

ChIP-seq and ChIP-nexus were prepared essentially as described [Shukla et al. 2018]. For details, see the Supplemental Material. The accession number of the sequencing data reported for Wellcome Centre for Cell Biology (203149).

Acknowledgments

We thank members of the Allshire laboratory for advice and useful suggestions. We thank Sito Torres-Garcia for running the ChIP samples on MiniSeq system. We thank Dominik Hoelter for critical reading of the manuscript. This research was supported by a Wellcome Principal Research Fellowship (103139), and Wellcome Senior Research Fellowship (110850) to J.R.; a Wellcome Centre for Cell Biology (203149), and Wellcome Senior Research Fellowship (108504) to J.R.; a Wellcome Senior Research Fellowship (103139), and Wellcome Centre for Cell Biology (203149).


References


Hap2–Ino80-facilitated transcription promotes de novo establishment of CENP-A chromatin

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Genes Dev. published online January 9, 2020
Access the most recent version at doi:10.1101/gad.332536.119

Supplemental Material
http://genesdev.cshlp.org/content/suppl/2020/01/06/gad.332536.119.DC1

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