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**THE EXPANDING UNIVERSE OF COHESIN FUNCTIONS: A NEW GENOME
STABILITY CARETAKER INVOLVED IN HUMAN DISEASE AND CANCER**

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ABSTRACT

Cohesin is responsible for sister chromatid cohesion, ensuring the correct chromosome segregation. Beyond this role, cohesin and regulatory cohesin genes seem to play a role in preserving genome stability and gene transcription regulation. DNA damage is thought to be a major culprit for many human diseases, including cancer. Our present knowledge of the molecular basis underlying genome instability is extremely limited. Mutations in cohesin genes cause human diseases such as the Cornelia de Lange syndrome and the Roberts syndrome/SC phocomelia, and all the cell lines derived from affected patients show genome instability. Cohesin mutations have also been identified in colorectal cancer. Here, we will discuss the human disorders caused by the alterations of cohesin function, with emphasis on the emerging role of cohesin as a genome stability caretaker.

Key words: Cohesin, genome instability, cancer, Cornelia de Lange syndrome, Roberts syndrome

OVERVIEW OF COHESIN FUNCTIONS

Canonical role of cohesin

The discovery of the cohesin complex has led to a breakthrough in clarifying the “cohesive force” in play during mitosis in holding the sister chromatids together and ensuring correct chromosome segregation. Cohesin is composed of four subunits, a pair of SMC proteins, SMC1A (MIM# 300040) and SMC3 (MIM# 606062), which are members of the Structural Maintenance of Chromosome family, and two non-SMC proteins, RAD21/Scc1 (MIM# 606462) and STAG/Scc3/Sa (Table 1) [Michaelis et al., 1997]. In vertebrates, there are two closely related Scc3 homologs, called STAG1 (MIM# 604358) and STAG2 (MIM# 604359) [Losada et al., 2000; Sumara et al., 2000]. In addition, a meiotic isoform is also present, named STAG3 (MIM# 608489) [Prieto et al., 2001]. SMC proteins are characterized by a globular hinge domain flanked by two α -helical domains (Figure 1A) which fold back on themselves at the hinge, forming a long antiparallel α -helical coiled coil arm that brings the N and C termini together. The N-terminal contains the Walker A box (or P-loop) which binds ATP. The C-terminal holds the Walker B, binding to DNA. SMC1A and SMC3 dimerize at the hinge domains, forming a V-shaped structure through hydrophobic interactions. Basically, the cohesin complex acts as a tripartite ring in which SMC1A and SMC3 are connected by their hinge domains on one side, and RAD21 closes the ring by connecting the SMC1A and SMC3 head domains on the other side [Anderson et al., 2002; Haering et al., 2002] (Figure 2). The cohesin ring shape supports the model where interaction between cohesin and DNA is topological, the so-called “ring” or “embrace” model. According to this model, cohesin topologically encircles sister chromatids. The cohesin opens at the head domain followed by the sister chromatid entering the ring and

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4 becoming topologically entrapped when RAD21 locks the ring [Gruber et al., 2006; Gruber et
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6 al., 2003; Haering, et al., 2002; Haering et al., 2004; Ivanov and Nasmyth, 2007]. Transient
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8 dissociation of SMC hinge domains also seems to contribute towards the entry of DNA into the
9
10 cohesin ring [Gruber et al., 2006]. Several alternative models, as well as the bracelet,
11
12 oligomerization and snap models have been proposed as the molecular basis of sister chromatid
13
14 cohesion [Diaz-Martinez et al., 2008; Guacci 2007; Huang et al., 2005; Milutinovich and
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16 Koshland, 2003]. These models have stimulated the research in this field and the true mechanism
17
18 may be a combination of those proposed. The cohesin binding to chromatin is dynamic and
19
20 occurs during the G1/S phase in the budding yeast or in the telophase of the previous cell cycle
21
22 in vertebrates [Haering et al., 2004]. In yeast, cohesin binds along chromosome arms every 10-20
23
24 kb, while its density is higher at centromeric regions [Glynn et al., 2004; Kogut et al., 2009;
25
26 Lengronne et al., 2004]. By contrast, in *Drosophila* the cohesin binding regions cover from a few
27
28 kilobases up to 100 kb in length [Misulovin et al., 2008]. Though the chromosome arm
29
30 dissociation process has yet to be fully understood, removal of cohesin begins in the prophase
31
32 and is completed by the anaphase. In the first step, RAD21 and STAG subunits are
33
34 phosphorylated by Polo-like kinase 1, causing the dissociation of the cohesin only along the
35
36 chromosome arms [Hauf et al., 2005], while the bulk of centromeric cohesin remains unchanged
37
38 [Waizenegger et al., 2000]. Once chromosomes are bi-oriented on the mitotic spindle at
39
40 anaphase, cohesin is completely removed from chromosomes by the separase protein (MIM#
41
42 604143) that cleaves RAD21, triggering sister chromatid disjunction. Initially, separase is
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44 inactivated through an association with securin (MIM# 604147), which is released after
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46 degradation through the ubiquitin dependent proteolysis pathway [Hauf et al., 2001; Uhlmann et
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4 al., 2000]. This model suggests that cohesin, preserved from degradation by separase during the
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6 prophase, can be loaded onto chromatin just after the restoration of the nuclear membrane.
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9 10 11 12 **Cohesin regulatory factors** 13

14 Cohesin interacts with several other proteins contributing towards its function (Table 1).
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16
17 The loading of cohesin onto chromatin requires NIPBL activity (MIM# 608667, homolog of
18
19 fungal *Scs2* and *Drosophila* Nipped-B). It has been speculated that NIPBL may be involved in
20
21 the activation of SMC ATPase and chromatin remodeling [Arumugam et al., 2003; Jahnke et al.,
22
23 2008]. PDS5A (MIM# 613200) and PDS5B (MIM# 605333) proteins are essential for the
24
25 association of cohesin with chromatin and sister chromatid cohesion. Their amino acid sequences
26
27 are conserved during evolution and are characterized by HEAT repeats which promote protein
28
29 interaction [Panizza et al., 2000]. The presence of two PDS5 and STAG proteins renders possible
30
31 the existence of four different types of cohesin containing either STAG1 or STAG2 and either
32
33 PDS5A or PDS5B [Losada et al., 2005; Sumara et al., 2000]. Cohesin is also associated with
34
35 WAPL; and like the PDS5 proteins, WAPL (MIM# 610754) also contains motifs which promote
36
37 protein-protein interaction. In fact, it has been shown that the FGF motifs of the WAPL protein
38
39 allow the physical interaction with PDS5 and cohesin subunits [Shintomi and Hirano, 2009]. It is
40
41 thought that WAPL is involved in the process of removing cohesin from chromatin [Gandhi et
42
43 al., 2006; Kueng et al., 2006]. ESCO2 (MIM# 609353) is involved in the establishment of
44
45 bridges between chromatid sisters during the cell cycle [Ivanov et al., 2002; Skibbens et al.,
46
47 1999; Toth et al., 1999]. It is also involved in the SMC3 acetylation [Heidinger-Pauli et al.,
48
49 2009; Zhang et al., 2008a], necessary for replication fork progression [Terret et al., 2009].
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51 Sororin (MIM# 609374) is the last identified protein known to be involved in cohesin activity.
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4 Data regarding this protein are limited; however, it has been hypothesized that it is involved in
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6 sister chromatid cohesion [Rankin et al., 2005; Schmitz et al., 2007]. It is clear that cohesin
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8 activity is tightly regulated and it is possible that new regulatory proteins will be identified in the
9
10 near future.
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13 14 15 16 **NON CANONICAL ROLE OF COHESIN: GENE EXPRESSION REGULATION**

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18 There is increasing experimental evidence suggesting that cohesin plays a part in the regulation
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20 of gene expression. The first proof that cohesin factors regulate gene expression comes from
21
22 studies on the *Drosophila Ultrabithorax* and *Cut* genes which are involved in many
23
24 developmental processes [Rollins et al., 1999]. In fact, the expression depends on Nipped-B
25
26 which might facilitate the interaction between promoter and remote enhancers possibly by
27
28 regulating chromosome architecture. Since Nipped-B acts as a cohesin regulatory protein, it was
29
30 hypothesised that cohesin would have the same effect as Nipped-B on the gene expression
31
32 regulation. Surprisingly, the inhibition of *Smc1a*, *Rad21* and *Sa* led to an increase of *Cut*
33
34 expression [Dorsett et al., 2005; Rollins et al., 2004]. These findings highlighted a possible role
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36 of cohesin as an insulator, inhibiting enhancer-promoter communication in *Cut*, and suggested
37
38 that *Nipped-B* promotes enhancer-promoter interaction by altering cohesin binding to chromatin
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40 [Rollins et al., 2004]. Notably, cohesin contributes to the insulator activity of the CCCTC
41
42 binding factor (CTCF), a zinc finger DNA-binding protein that is evolutionary conserved
43
44 [Parelho et al., 2008; Rubio et al., 2008; Stedman et al., 2008; Wendt et al., 2008]. However,
45
46 recent data suggest that the manner in which cohesin regulates gene expression is more complex.
47
48 The fact that the depletion of either *Rad21* or *Smc3* in Zebrafish results in the reduced expression
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50 of *Runx* genes, involved in the activation of hematopoietic and neurogenic genes has been
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4 demonstrated [Horsfield et al., 2007]. Studies in *Drosophila* show that cohesin can exert
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6 opposing effects, both positive and negative, on gene expression [Schaaf et al., 2009]. These
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8 results are consistent with gene expression data obtained in Cornelia de Lange syndrome (CdLS;
9
10 MIM#s 122470, 300590, 610759) cell lines and in *Nipbl*^{+/-} mutant mice where many genes are
11
12 down- and up-regulated [Kawauchi et al., 2009; Liu et al., 2009b]. Beyond its role in sister
13
14 chromatid cohesion, emerging data show that the activity of cohesin and cohesin regulatory
15
16 factors is critical for the proper development of organisms by regulating gene expression in
17
18 multiple ways.
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23 Mutations in *NIPBL*, *SMC1A* and *SMC3* cause CdLS while mutations in *ESCO2* are associated
24
25 with Roberts syndrome (RBS; MIM# 268300) /SC phocomelia (MIM# 269000) [Deardorff et
26
27 al., 2007; Krantz et al., 2004; Musio et al., 2006; Schule et al., 2005; Tonkin et al., 2004; Vega et
28
29 al., 2005]. CdLS and RBS are collectively termed “cohesinopathies” [reviewed in Liu and
30
31 Krantz, 2008]. CdLS is the most frequent disease among those due to cohesion pathway defects.
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34 Though the molecular pathobiology of CdLS is largely unknown, it is noteworthy that the
35
36 dysregulation of gene expression likely represents the underlying pathogenesis of CdLS. It has
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38 recently been discovered, by using a genome-wide approach to study gene expression, that
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40 alteration of a restricted number of genes which can be considered as CdLS biomarkers are
41
42 capable of differentiating CdLS from non-CdLS samples. Their expression levels also correlate
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44 with the phenotypic severity of the disorder [Liu et al., 2009b]. In addition, small changes in
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46 *Nipbl* activity affect appropriate development in the *Nipbl*^{+/-} mouse model. In particular, gene
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48 expression profiling demonstrates that *Nipbl* deficiency leads to modest but significant
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50 transcriptional dysregulation of many genes [Kawauchi et al., 2009].
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4 Cohesinopathy cell lines show both spontaneous and induced genome instability. In addition,
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6 mutations or dysregulation of cohesin and regulatory cohesin genes are associated with human
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8 cancer (see below). These observations suggest that the cohesin pathway may be involved in
9
10 genome stability maintenance and tumorigenesis. This review focuses specifically on the
11
12 emerging role of cohesin as a new genome stability caretaker involved in human disease and
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16 cancer.
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20 21 **COHESIN AND GENOME INSTABILITY**

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23 Genome instability has been discovered as one of the major factors responsible for human
24
25 diseases, including cancer. It manifests as point mutations, gene amplifications, aneuploidies (i.e.
26
27 the gain or loss of entire chromosomes), deletions and translocations. The genomic stability
28
29 depends on an intricate machinery of DNA repair mechanisms, correct chromosome segregation
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31 pathways and the activation of cell cycle checkpoints in order to arrest cell cycle progression.
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34 The initial confirmation that cohesin is involved in genome stability came from studies in *S.*
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36 *pombe*. *Scc1* mutants are hypersensitive to DNA damage [Birkenbihl and Subramani, 1992],
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38 suggesting that cohesin plays an important function in the DNA damage response. In recent
39
40 years, ample experimental evidence supports the notion that cohesin is also involved in genome
41
42 stability maintenance in human cells. SMC1A was shown to be the target of the ATM kinase
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44 with phosphorylation of SMC1A-Ser957 and SMC1A-Ser966, occurring in an ATM dependent
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46 manner after ionizing irradiation [Kim et al., 2002; Yazdi et al., 2002]. Subsequently, it has been
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48 shown that NBS1 and BRCA1 are required for the recruitment of activated ATM at the sites of
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50 DNA double strand breaks, and that this process is necessary for the phosphorylation of SMC1A
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52 by ATM following irradiation [Kitagawa et al., 2004]. We showed that SMC1A phosphorylation
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4 can be ATM-independent, depending on the type of DNA damage. Moreover, we found that
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6 SMC1A is phosphorylated on Ser966 by ATR after replication stress induced by aphidicolin,
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8 while no phosphorylation occurred on Ser957 [Musio et al., 2005]. The finding that ATM is not
9
10 involved in the SMC1A phosphorylation following replication stalling is not surprising because
11
12 it seems to be specifically involved in response to irradiation [Kim et al., 2002; Yazdi et al.,
13
14 2002]. These observations suggest that cohesin participates in two different pathways, triggering
15
16 a specific response to different DNA damage types that challenge genome stability.
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19
20 The heterodimer SMC1A-SMC3 is also a member of a mammalian protein complex, called
21
22 recombination complex RC-1, which promotes DNA recombination [Jessberger et al., 1996;
23
24 Stursberg et al., 1999]. There are three additional members belonging to the RC-1 complex:
25
26 DNA ligase III, DNA polymerase ϵ , and unidentified structure-specific DNA endonuclease. It is
27
28 thought that the RC-1 complex catalyses several recombination-related reactions such as the
29
30 homology-dependent transfer of DNA between two dsDNA molecules, DNA single-strand re-
31
32 annealing, and the repair of gaps or deletions in dsDNA substrates [reviewed in Jessberger,
33
34 2002].
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38 Following DNA damage, cohesin accumulates in a large 50 kb domain that surrounds the
39
40 damage site [Strom et al., 2004; Unal et al., 2004] and SMC1A-SMC3 are phosphorylated [Kim,
41
42 et al., 2002; Luo et al., 2008; Yazdi et al., 2002]. Cohesin's ability to establish cohesion *de novo*
43
44 is essential for DNA damage repair [Strom, et al., 2004; Unal et al., 2004] and we found that fork
45
46 stalling induced an increase in SMC1A synthesis levels [Musio et al., 2005]. These findings
47
48 suggest that the cohesin increase and its accumulation can stabilize the broken sites, acting as
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50 scaffolding to improve the recruitment of DNA repair machinery. Furthermore, the
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4 phosphorylation of cohesin proteins may be required for activation of cell cycle checkpoints,
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6 allowing cell cycle arrest and DNA repair.
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10 11 **COHESIN AND CANCER**

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14 Genome instability is thought to play a pivotal role in the tumorigenic process and it is
15
16 considered a hallmark of cancer cells. So far, only a limited number of genes thought to be
17
18 involved in the maintenance of genome instability have been identified as having somatic
19
20 mutations in human cancer. The recent finding that human colorectal cancers cells carry
21
22 mutations in cohesin genes (Figure 3) further support the notion that cohesin is involved in
23
24 genome instability and cancer. Eleven somatic mutations have been identified in more than 130
25
26 colorectal cancer cases. Six of them map to three core cohesin genes (*SMC1A*, *SMC3* and
27
28 *STAG3*), four to a regulatory cohesin gene (*NIPBL*) and one to *RNF20*, a non related cohesin
29
30 gene [Barber et al., 2008]. *SMC1A* and *NIPBL* account for 8 out of 10 mutations (Figures 3A,
31
32 3B). All *SMC1A* mutations are missense (Supp. Table S1): c.1186T>C, c.1300C>T, c.1680C>G
33
34 and c.3556G>A leading to Phe396Leu, Arg434Trp, Ile560Met and Val1186Ile changes,
35
36 respectively. The first two mutations map to the coiled-coil domain, the third to the hinge
37
38 domain and the last to carboxy terminal P-loop NTPase domain (Figure 3A). It is interesting to
39
40 note that *SMC1A* mutations are only missense in both *SMC1A*-mutated CdLS patients (see
41
42 below) and in cancer cells, suggesting that frameshift and nonsense mutations are lethal. The
43
44 four mutations in *NIPBL* are: c.1435C>T, c.2967_2968 insT, c.1660C>T, c.5378T>A leading to
45
46 Arg479X, Val992fsX, Gln664X and Met1793Lys changes (Figure 3B, Supp. Table S1). Finally,
47
48 *SMC3* and *STAG3* show the mutations c.2635C>T and c.24117C>T (Supp. Table S1), which
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50 cause the Arg879X (Figure 3C) and Ile795Thr (Figure 3D) amino acid changes, respectively.
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4 The majority of these mutations are heterozygous nonsense mutations which disrupt protein
5 function through the creation of stop codons. This finding raises the possibility that nonsense
6 mutations might be more predisposed to cancer than missense mutations. These mutations could
7 dysregulate cohesin activity by preventing correct protein association, by altering the SMC
8 ATPase activity or affecting the dynamic displacement of cohesin from chromatin. Colorectal
9 cancer cells are characterized by chromosomal instability, resulting in chromosome gain or loss.
10 It is possible to argue that abnormal cohesion pathway activity leads to chromosome
11 missegregation and chromosome instability. This hypothesis is supported by the observation that
12 colorectal cancer cells exhibit up to 100-fold higher rates of missegregation than normal cells
13 [Lengauer et al., 1997]. Therefore chromosomal instability in colorectal cancer cells could be a
14 direct consequence of cohesin mutations.
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In addition to core cohesin genes, there is increasing evidence also linking cohesin regulatory genes to tumorigenesis. The overexpression of *WAPL* correlates with the progression of cervical cancer malignancy (Table 1), and cells overexpressing *WAPL* develop tumors after injection into nude mice [Oikawa et al., 2004]. *Separase* is found to be significantly overexpressed in human breast cancer [Zhang et al., 2008b], osteosarcoma and prostate cancer (Table 1) [Meyer et al., 2009]. Its induction leads to premature separation of chromatids, lagging chromosomes with specific chromosome aneuploidies [Zhang, et al., 2008b]. Finally, *ESCO2* is up-regulated in more aggressive melanomas [Ryu et al., 2007], *Securin* (also known as proto-oncogene pituitary tumor transforming gene, *PTTG*) is overexpressed in pituitary tumors [Zou et al., 1999] and *RAD21* is overexpressed in breast [Atienza et al., 2005; Oishi et al., 2007] and prostate cancer (Table 1) [Porkka et al., 2004]. *ESCO2* and *Securin* promote cohesin function while *WAPL* and *Separase* antagonize this function. Therefore the fact that those genes are overexpressed in

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4 cancer suggests that cohesin and positive and negative regulatory proteins have a complex
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6 relationship with tumorigenesis. Indeed, in some cases these genes might act as oncogenes and in
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8 others as tumor suppressor genes. At present, the genetic factors which determine these opposite
9
10 effects are not known.
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14 Cancer is thought to be a multistep process in which abnormalities in proto-oncogenes and tumor
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16 suppressors predispose cells to the acquisition of many other genetic changes which are
17
18 responsible for the acquisition of the full malignant phenotype. Cohesin could play an important
19
20 role in genome instability and tumorigenesis, and chromosome aneuploidy due to defects in
21
22 correct chromosome segregation could cause the loss of heterozygosity of tumor suppressor
23
24 genes or the improper activation of proto-oncogenes. SMC1A associates with mitotic
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26 microtubules at the spindle pole, and SMC1A imbalance leads to multipolar spindles [Wong and
27
28 Blobel, 2008]. Furthermore, the inhibition of cohesin genes by RNA interference or antisense
29
30 oligonucleotide causes aneuploidy and micronuclei formation in dividing cells [Barber, et al.,
31
32 2008; Musio et al., 2003]. These observations suggest that the association of SMC1A with
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34 microtubules is required for proper segregation, and its dysfunction leads to aneuploidy. In
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36 addition, cohesin mutations could dysregulate the expression of proto-oncogenes or tumor
37
38 suppressor genes, triggering uncontrolled cell proliferation and the development of malignant
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40 cells. In human cells, cohesin depletion leads to changes in transcription at the imprinted
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42 *H19/IGF2* locus [Nativio et al., 2009; Wendt et al., 2008]. Several lines of evidence support the
43
44 hypothesis that the altered imprinting process at *H19/IGF2* locus is important in tumorigenesis
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46 [Feinberg, 1999; Pollak 2008]. It is therefore possible that defects in cohesin affect this imprinted
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48 domain and the genes within it.
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COHESINOPATHIES AND GENOME INSTABILITY

CdLS consists of characteristic facial features, hirsutism, gastroesophageal reflux, upper extremity malformations ranging from small hands to severe forms of oligodactyly and truncation of the forearms and mental retardation. Approximately 60% of CdLS probands carry a *NIPBL* mutation, most of which are point mutations or small insertions and deletions in coding regions or splice junctions. It is thought that these mutations produce either abnormal full length or truncated NIPBL proteins [Gillis et al., 2004]. A subset of CdLS probands carry mutations in the *SMC1A* and *SMC3* genes [Deardorff et al., 2007; Musio et al., 2006]. *SMC1A* is responsible for 5% of CdLS cases whereas up until now only a single proband has been found to have a mutation in *SMC3*. The *PDS5B* gene could be an additional CdLS gene. Moreover, the *Pds5B* knockout mice show several features reminiscent of the CdLS phenotype, and the genetic screening of a large cohort of CdLS patients allowed the identification of a patient carrying a mutation in the *PDS5B* gene. However, the same mutation has been found in unaffected relatives making the role of this mutation in CdLS less clear [Zhang et al., 2009].

Collectively, a total of 23 mutations in the *SMC1A* and *SMC3* core cohesion genes have been identified in CdLS (Supp. Table S1). All mutations are missense or small in-frame deletions (3 or 15 nucleotides deletion) [Deardorff et al., 2007; Liu et al., 2009a; Mannini et al., 2010]. The *SMC3* amino acid change maps to the coiled coil domain (Figure 1B) whereas the *SMC1A* amino acid changes encompass all gene domains (Figure 1C) and do not affect the synthesis of the *SMC1A* protein [Liu et al., 2009a; Musio et al., 2006; Revenkova et al., 2009]. *SMC1A* maps to Xp11.2 which escapes X chromosome inactivation [Brown et al., 1995; Tsuchiya and Willard, 2000]. Both hemizygous male and heterozygous female CdLS patients have been identified [Deardorff et al., 2007; Liu et al., 2009a; Musio et al., 2006]; it is likely that *SMC1A* mutations

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4 act as a dominant negative in females [Liu et al., 2009a; Mannini et al., 2010; Revenkova et al.,
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7 2009].

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9 RBS is an autosomal recessive developmental disorder characterized by pre-and post-natal
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11 growth retardation, tetraphocomelia, and craniofacial abnormalities. The causative gene of RBS
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13 is *ESCO2* which encodes a protein belonging to the highly conserved *ECO1/CTF7* family of
14
15 acetyltransferase which is involved in regulating sister chromatid cohesion [Vega et al., 2005].
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19 Most *ESCO2* mutations are expected to cause stop codons that result in truncated protein or
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21 mRNA instability due to nonsense-mediated mRNA decay [Gordillo et al., 2008].
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25 All cohesinopathy cell lines are characterized by genome instability. A number of chromosomal
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27 rearrangements (balanced de novo translocations, duplications, deletions) have been reported in
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29 CdLS probands. The molecular characterization of the chromosomal rearrangement
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31 t(5;13)(13.1;q12.1) allowed the identification of the *NIPBL* gene [Krantz et al., 2004]. CdLS cell
32
33 lines show a statistically significant increase of both spontaneous and induced chromosome
34
35 aberrations through genotoxic treatments such as irradiation and Mitomycin C [Revenkova et al.,
36
37 2009; Vrouwe et al., 2007]. It is possible that dysregulation of cohesion activity triggers
38
39 spontaneous genome instability and confers sensitivity to genotoxic treatments. Increased DNA
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41 damage seems to be a common feature of CdLS, suggesting that genome instability analysis and
42
43 genotoxic agent treatments can be a useful diagnostic assay and can serve as a classification tool.
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46
47 We found that spontaneous genome instability analysis is able to discriminate among the
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49 different types of *SMC1A* mutations. In fact, CdLS patients carrying mutations in the head
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51 domain show higher frequency of chromosome aberrations than patients with mutations in the
52
53 other domains [Revenkova et al., 2009].
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57 RBS cell lines also display genome instability occurring as chromosome aneuploidies
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4 andmicronuclei formation, in addition to poor growth, reduced plating efficiency and lower
5 density for confluent cultures [Jabs et al., 1991; Musio et al., 2004]. Cells from RBS patients
6 exhibit a characteristic abnormality of their constitutive heterochromatin, described as
7 precocious sister chromatid separation and puffing of the peri- and para-centromeric regions of
8 chromosomes 1, 9 and 16. Less clear is the situation in CdLS; a study reported precocious sister
9 chromatid separation [Kaur et al., 2005; Musio, et al., 2004], however more recent studies
10 showed no cohesion defects in CdLS cell lines [Castronovo et al., 2009; Liu et al., 2009b;
11 Revenkova et al., 2009; Tonkin et al., 2004; Vrouwe et al., 2007]. Similar observations have also
12 been reported in *Nipbl*^{+/-} mice [Kawauchi et al., 2009] and *Nipped-B* mutant fly [Rollins et al.,
13 2004].

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15 To date, no mutations have been identified in other cohesin pathway genes, their effect on
16 cohesion can be inferred only by *in vitro* treatments. The depletion of *WAPL* prevents the
17 resolution of sister chromatids, while its overexpression induces premature sister chromatid
18 separation [Gandhi et al., 2006; Kueng et al., 2006]. The inactivation of Sororin leads to
19 precocious sister chromatid separation [Schmitz et al., 2007] and the inhibition of Separase
20 prevents sister chromatid separation leading to diplo- or quadruplochromosomes, indicating that
21 sister chromatids were not disjoined in the previous cell cycle [Wirth et al., 2006].

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23 Cohesinopathy probands have a low rate of cancer; up till now only a few cases of cancer have
24 been described. In fact, four RBS patients developed oculomotor nerve cavernous angiomas,
25 malignant melanoma and rhabdomyosarcoma [Feingold 1992; Ogilvy et al., 1993; Parry et al.,
26 1986; Wenger et al., 1988] while some CdLS patients developed esophageal adenocarcinoma
27 [reviewed in Kline et al., 2007]. It is possible to speculate that genomic instability in CdLS leads
28 to the formation of certain tumors. Consistent with this notion is the observation that trisomy 21
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4 promotes the development of leukemia while the frequency of solid cancers is low in Down
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6 syndrome patients [Satgé et al., 1998]. Further epidemiologic studies will address the argument
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8 as to whether cohesinopathies lead to cancer development.
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11 12 13 14 **CONCLUSION**

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18 It is becoming clearer that the role of cohesin is not limited to holding sister chromatids together
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20 and ensuring correct chromosome segregation. More recent works have revealed that the
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22 universe of cohesin functions is rapidly expanding. In fact, cohesin is essential for gene
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24 expression regulation, cell cycle control, DNA damage response and genome stability
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26 maintenance. Mutations or dysregulation of cohesin and regulatory cohesin genes are associated
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28 to cohesinopathies and cancer. In addition, cohesinopathy cell lines show both spontaneous and
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30 induced genome instability, and in some cases it is responsible for the CdLS etiopathology.
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33 However, whether genome instability is a cause or a consequence of cohesinopathies is still open
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35 to debate. The dysfunction of cohesin pathways can cause missegregation, leading to
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37 chromosome aneuploidy, a hallmark of cancer cells, and improper activation or inhibition of
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39 proto-oncogene or tumor suppressor genes, respectively. However, it has recently been shown
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41 that aneuploidy represents a barrier towards cancer development [Williams et al., 2008]. It is
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43 possible that within a population of genomic-deregulated cells those with tolerated aneuploidy
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45 and high proliferative capacity are selected, leading to cancer development [Williams et al.,
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2008]. Altogether this evidence supports the intriguing notion that cohesin may represent a new
genome stability caretaker in mammalian cells involved in human disease and cancer. It is
becoming increasingly clear that cell lines derived from cohesinopathy probands suffer from

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4 defects in surveillance mechanisms, leading to genome instability. Cohesin defects and/or
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6 genome instability, in addition to dysregulation of gene expression resulting from mutations in
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8 cohesin genes could account for the growth retardation as well as developmental defects by
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10 affecting the number of cells in developing tissue, leading to specific cohesinopathy phenotypes.
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21 **FIGURE LEGENDS**

22
23 **Figure 1.** SMC core cohesin protein organization and CdLS. (A) Schematic organization of
24 SMC proteins. They contain five distinct domains: N-terminal (or P-loop NTPase), a hinge motif
25 flanked by two coiled coil regions and a C-terminal (or P-loop NTPase); (B) Mapping of the
26 amino acid change identified in a CdLS patient in the SMC3 protein; (C) Localization onto the
27 SMC1A protein of the twenty two amino acid mutations identified in CdLS.
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37 **Figure 2.** Structure of cohesin complex. The somatic vertebrate core cohesin complex consists of
38 two SMC subunits, namely SMC1A and SMC3, and two non SMC subunits, RAD21 and
39 STAG. Each SMC subunit forms a rod shaped protein with a globular hinge domain at one end
40 and an ATP nucleotide binding domain at the other. SMC1A and SMC3 are connected by their
41 hinge domains on one side and the RAD21 closes the ring by connecting SMC1A and SMC3
42 head domains on the other side, creating a huge tripartite ring.
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53 **Figure 3.** Cohesin and regulatory cohesin proteins and colorectal cancer. Localization of the four
54 amino acid changes identified in both SMC1A (A) and NIPBL (B), and the single change
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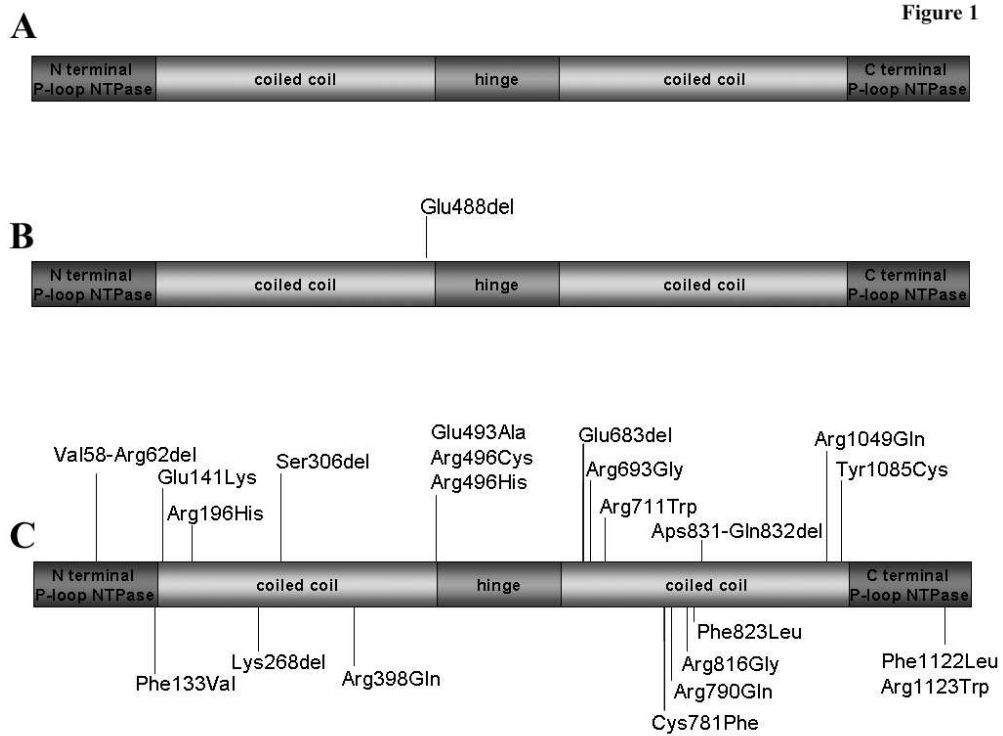
detected in SMC3 (C) and STAG3 (D). The protein length is not in scale.

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Table 1. Components of cohesin pathway and their involvement in human diseases

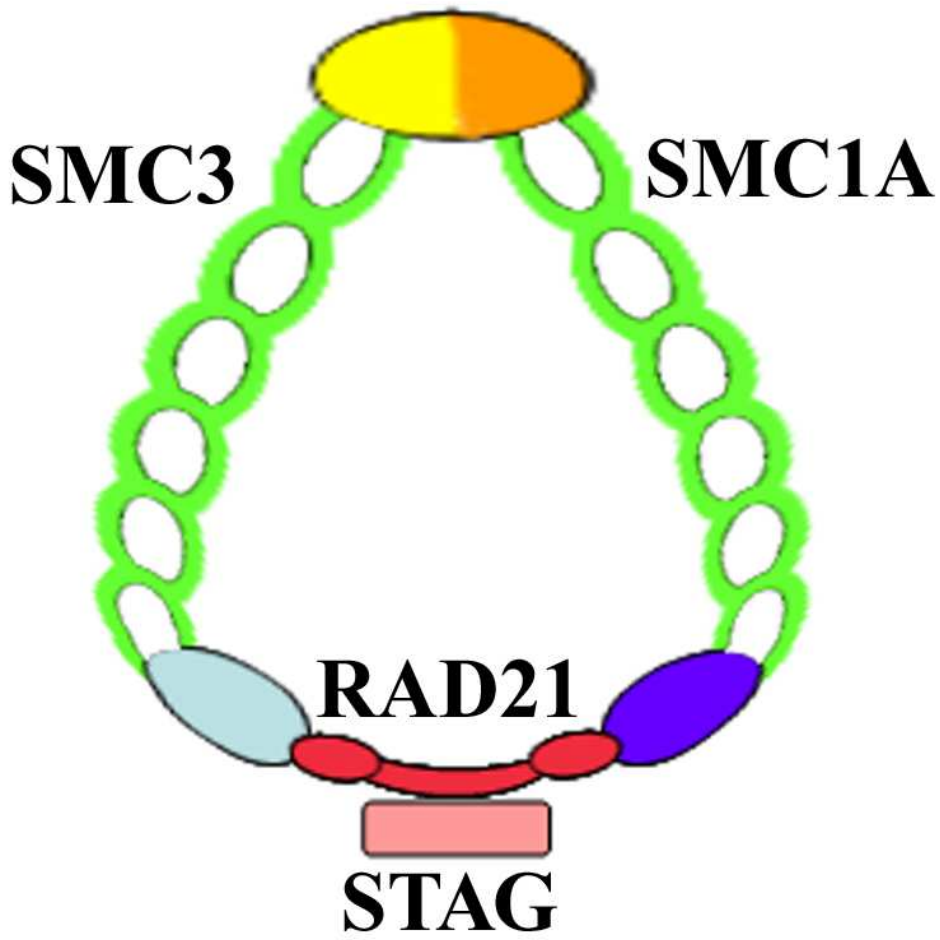
Gene	OMIM	Role	Disease
<i>SMC1A</i>	300040	Core cohesin member	CdLS Colorectal cancer
<i>SMC3</i>	606062	Core cohesin member	CdLS Colorectal cancer
<i>RAD21</i>	606462	Core cohesin member	Breast cancer Prostate cancer
<i>STAG1</i>	604358	Core cohesin member	
<i>STAG2</i>	604359	Core cohesin member	
<i>STAG3</i>	608489	Core cohesin member	Colorectal cancer
<i>ESCO2</i>	609353	Cohesin regulatory, sister chromatid cohesion	RBS Melanoma cancer
<i>NIPBL</i>	608667	Cohesin regulatory, cohesin loading	CdLS Colorectal cancer
<i>PDS5A</i>	613200	Cohesin regulatory, sister chromatid cohesion	
<i>PDS5B</i>	605333	Cohesin regulatory, sister chromatid cohesion	CdLS

<i>PTTG1</i> (Securin)	604147	Cohesin regulatory, sister chromatid dissociation	Pituitary cancer
<i>ESPL1</i> (Separase)	604143	Cohesin regulatory, sister chromatid dissociation	Breast cancer Osteosarcoma Prostate cancer
<i>CDCA5</i> (Sorotin)	609374	Cohesin regulatory, sister chromatid cohesion	
<i>WAPL</i>	610754	Cohesin regulatory, cohesin dissociation	Cervical Cancer



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Figure 2



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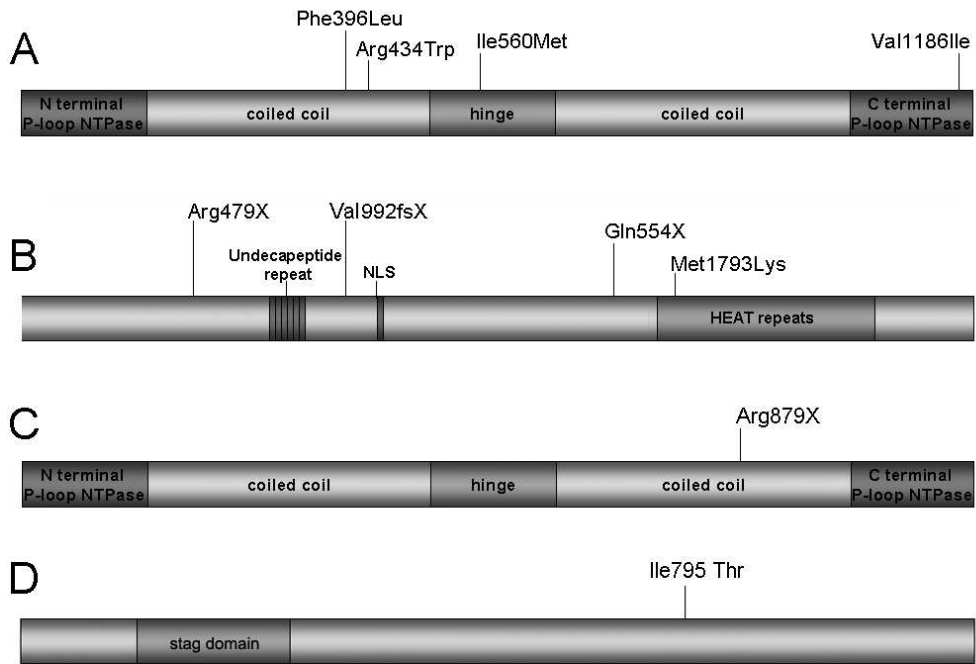


Figure 3

128x99mm (200 x 200 DPI)

review

Supp. Table S1. Mutational spectrum of the *SMC1A*, *SMC3*, *STAG3* and *NIPBL* in human disease

Gene	Nucleotide changes*	Effect on amino acid	Disease
<i>SMC1A</i>	c.173_187del15	p.Val58-Arg62del	CdLS
	c.397T>G	p.Phe133Val	CdLS
	c.421G>A	p.Glu141Lys	CdLS
	c.587G>A	p.Arg196His	CdLS
	c.802_804del3	p.Lys268del	CdLS
	c.916_918del3	p.Ser306del	CdLS
	c.1193G>A	p.Arg398Gln	CdLS
	c.1478A>C	p.Glu493Ala	CdLS
	c.1486C>T	p.Arg496Cys	CdLS
	c.1487G>A	p.Arg496His	CdLS
	c.2046_2048del3	p.Glu683del	CdLS
	c.2077C>G	p.Arg693Gly	CdLS
	c.2131C>T	p.Arg711Trp	CdLS
	c.2342G>T	p.Cys781Phe	CdLS
	c.2369G>A	p.Arg790Gln	CdLS
	c.2446C>G	p.Arg816Gly	CdLS
	c.2467T>C	p.Phe823Leu	CdLS
	c.2493_2495del3	p.Asp831- Gln832del	CdLS
	c.3146G>A	p.Arg1049Gln	CdLS
	c.3254A>G	p.Tyr1085Cys	CdLS
c.3364T>C	p.Phe1122Leu	CdLS	
c.3367C>T	p.Arg1123Trp	CdLS	
c.1186T>C	p.Phe396Leu	Colorectal cancer	
c.1300C>T	p.Arg434Trp	Colorectal cancer	
c.1680C>G	p.Ile560Met	Colorectal cancer	
c.3556G>A	p.Val1186Ile	Colorectal cancer	
<i>SMC3</i>	c.1464_1466del3	p.Phe488del	CdLS
	c.2635C>T	p.Arg879X	Colorectal cancer
<i>STAG3</i>	c.2384T>C	p.Ile795Thr	Colorectal cancer
<i>NIPBL</i>	c.1435C>T	p.Arg479X	Colorectal cancer
	c.2967_2968insT	p.Val992fsX	Colorectal cancer
	c.1660C>T	p.Gln554X	Colorectal cancer
	c.5378T>A	p.Met1793Lys	Colorectal cancer

* Nucleotide numbering reflects cDNA numbering with +1 corresponding to the A of the ATG translation initiation codon in the reference sequences NM_006306.2 (for *SMC1A*), NM_005445.3 (for *SMC3*), NM_012447.2 (for *STAG3*), NM_015384.3 (for *NIPBL*) according to journal guidelines (www.hgvs.org/mutnomen). The initiation codon is codon 1.