




The tumor suppressor *Hic1* maintains chromosomal stability independent of *Tp53*

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Abstract

Hypermethylated-in-Cancer 1 (Hic1) is a tumor suppressor gene frequently inactivated by epigenetic silencing and loss-of-heterozygosity in a broad range of cancers. Loss of *HIC1*, a sequence-specific zinc finger transcriptional repressor, results in deregulation of genes that promote a malignant phenotype in a lineage-specific manner. In particular, upregulation of the *HIC1* target gene *SIRT1*, a histone deacetylase, can promote tumor growth by inactivating *TP53*. An alternate line of evidence suggests that *HIC1* can promote the repair of DNA double strand breaks through an interaction with *MTA1*, a component of the nucleosome remodeling and deacetylase (NuRD) complex. Using a conditional knockout mouse model of tumor initiation, we now show that inactivation of *Hic1* results in cell cycle arrest, premature senescence, chromosomal instability and spontaneous transformation in vitro. This phenocopies the effects of deleting *Brcal*, a component of the homologous recombination DNA repair pathway, in mouse embryonic fibroblasts. These effects did not appear to be mediated by deregulation of *Hic1* target gene expression or loss of *Tp53* function, and rather support a role for *Hic1* in maintaining genome integrity during sustained replicative stress. Loss of *Hic1* function also cooperated with activation of oncogenic *KRas* in the adult airway epithelium of mice, resulting in the formation of highly pleomorphic adenocarcinomas with a micropapillary phenotype in vivo. These results suggest that loss of *Hic1* expression in the early stages of tumor formation may contribute to malignant transformation through the acquisition of chromosomal instability.

Introduction

Hypermethylated-in-Cancer-1 (HIC1) was discovered during a screen for highly methylated tumor suppressor genes on chromosome 17p [1]. *HIC1* resides immediately telomeric to *TP53* at 17p13.3, and encodes a BTB/POZ domain zinc finger transcriptional repressor closely related to the

PLZF family of proteins [1–5]. The locus also contains a *Tp53* response element, and two major CpG rich promoters that generate different alternatively spliced transcripts [1, 6–8]. Over the last decade, several groups have shown that epigenetic gene silencing and/or loss of heterozygosity of *HIC1* is one of the most common events in human cancer [9–12], and this is associated with poor outcomes in a wide variety of tumor types [12–17], including lung cancer [18].

Homozygous deletion of *Hic1* with a conventional mouse knockout approach results in mid-gestation embryonic lethality [19], whereas heterozygous mutants develop a range of spontaneous tumors in an age-dependent manner [7]. Furthermore, *Hic1* mutant mice demonstrate an accelerated tumor phenotype when crossed into established genetic models of colorectal cancer [20], medulloblastoma [21], and osteosarcoma [22].

The conventional model of *Hic1* function is based on the identification of transcriptional targets through a combination of *Hic1* re-expression in cancer cells and gene

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expression profiling [5, 21, 23–25]. Based on this premise, loss of *Hic1* expression through promoter hypermethylation results in aberrant overexpression of lineage-specific genes that promote or maintain the malignant phenotype [5]. In addition, *Hic1* also has been shown to attenuate the effect of oncogenic transcription factors complexes that mediate WNT [26] or STAT3 [24, 27] signaling.

One important transcriptional target of *Hic1* is the Sirtuin ortholog *Sirt1* [28]. Sirtuins belong to the NAD-dependent, trichostatin-insensitive class III histone deacetylases that mediate life span extension in response to caloric restriction in yeast [29]. Importantly, *Sirt1* actively deacetylates and inactivates *p53* [30], thus establishing a direct link between loss of *Hic1* and attenuation of *Tp53* signaling [28]. By contrast, mice carrying heterozygous mutations in both *Tp53* and *Hic1* in *cis* rapidly develop osteosarcomas in which the wild type copies of both genes are deleted [22], suggesting that loss of both genes predisposes to tumor development that cannot be fully explained through a *Hic1*-*Sirt1*-*p53* dependent mechanism.

To better define the function of *Hic1* in suppressing tumor initiation, we developed a conditional deletion mouse mutant to overcome the embryonic lethality of the *Hic1* knockout mouse, and bypass the reliance on stochastic promoter methylation of the wild type allele in *Hic1* heterozygous mutants [7].

Results and discussion

Growth arrest and premature senescence in *Hic1*-deficient mouse embryonic fibroblasts

Using targeted homologous recombination in mouse embryonic stem cells, we introduced *loxP* sites flanking Exon 2 of the *Hic1* locus (Fig. 1a). Mice homozygous for the conditional allele (hereafter *Hic1^{lox/lox}*) demonstrated no developmental phenotype, were not cancer prone, and were fertile (data not shown). To generate a conditional mutant model in mouse embryonic fibroblasts (MEFs), we crossed the *Hic1^{lox/lox}* mouse with a line in which a Cre recombinase transgene fused to the estradiol receptor has been introduced into the constitutively expressed ROSA locus (hereafter *EsrCre*) [31]. Ex-vivo treatment with tamoxifen induces activation and translocation of Cre recombinase resulting in *loxP* recombination with high efficiency.

Treatment of MEFs generated from *Hic1^{lox/lox} EsrCre* embryos (hereafter *Hic1KO*) with tamoxifen, followed by a 48 h incubation period confirmed deletion of Exon 2, which contains the entire coding region of the *Hic1* gene (Fig. 1b). Loss of *Hic1* protein expression in the same MEF model was also confirmed by Western blot analysis (Fig. 1c).

In contrast to *EsrCre* MEFs, tamoxifen treated *Hic1KO* MEFs displayed a marked G2/M arrest (Figs. 1d, e), and premature activation of senescence-associated beta-galactosidase (SA- β Gal) (Figs. 1f, g). This was unexpected, since *Hic1* is a known tumor suppressor gene, and because its capacity to prevent *Tp53* deacetylation through transcriptional repression of *Sirt1* would have predicted that *Hic1* deletion would phenocopy *p53* deletion in this model. Equally surprising was the pattern of gene expression in *Hic1KO* MEFs 48 h after tamoxifen treatment (Fig. 1h). Although an increase in the expression of the known *Hic1* target genes *Efnal* [24] and *Tlr2* [32] was observed, no changes in *Sirt1* were seen (Supplementary Table S1). Unexpectedly, gene expression microarray and gene ontology analysis revealed highly significant enrichment for pathways involved in the regulation of cell cycle, mitosis, and DNA replication consistent with the induction of cell cycle arrest (Figs. 1h, i; Supplementary Table S2). These data are resemble a phenomenon in MEFs known as “tumor suppressor inactivation-induced senescence”, best exemplified by inactivation of the breast cancer tumor suppressor gene *Brcal*, which results in overwhelming DNA damage as the result of replication-dependent double-strand break (DSB) formation, chromosomal instability and *Tp53*-dependent senescence [33, 34].

Immortalized *Hic1KO* MEFs are phenotypically distinct from *p53KO* MEFs

To determine whether the effects of *Hic1* deletion could be functionally separated from downregulation of *Tp53* function through upregulation of *Sirt1*, we employed a conditional *Tp53* knockout allele (hereafter *p53^{lox/lox}*) to generate MEFs derived from *p53^{lox/lox} EsrCre* embryos (hereafter *p53KO*). Embryos heterozygous for the *EsrCre* allele were used as controls (hereafter *EsrCre*). Serial passaging of *EsrCre*, *p53KO*, and *Hic1KO* MEFs using a modified 3T3 protocol demonstrated that deletion of *Hic1* can replicate the effect of loss of *Brcal* function in the MEF model (Fig. 2a). As expected, *p53KO* MEFs spontaneously immortalized with high efficiency, while control *EsrCre* cells escaped senescence with similar efficiency but in a much longer timeframe. By contrast, *Hic1KO* MEFs immortalized with low efficiency after a period of dormancy lasting over 60 days (Fig. 2a) in similar fashion to the *Brcal* knockout model [33].

One of the most rigorous tests of malignant transformation in the MEF model is the capacity of immortalized cells to grow as allografts in athymic nude mice [35]. To assess this, early passage immortalized MEF lines from each genotype were injected subcutaneously into the flanks of nude mice and observed. Fast growing *Hic1KO* tumors rapidly appeared within 3 weeks, whereas tumors derived

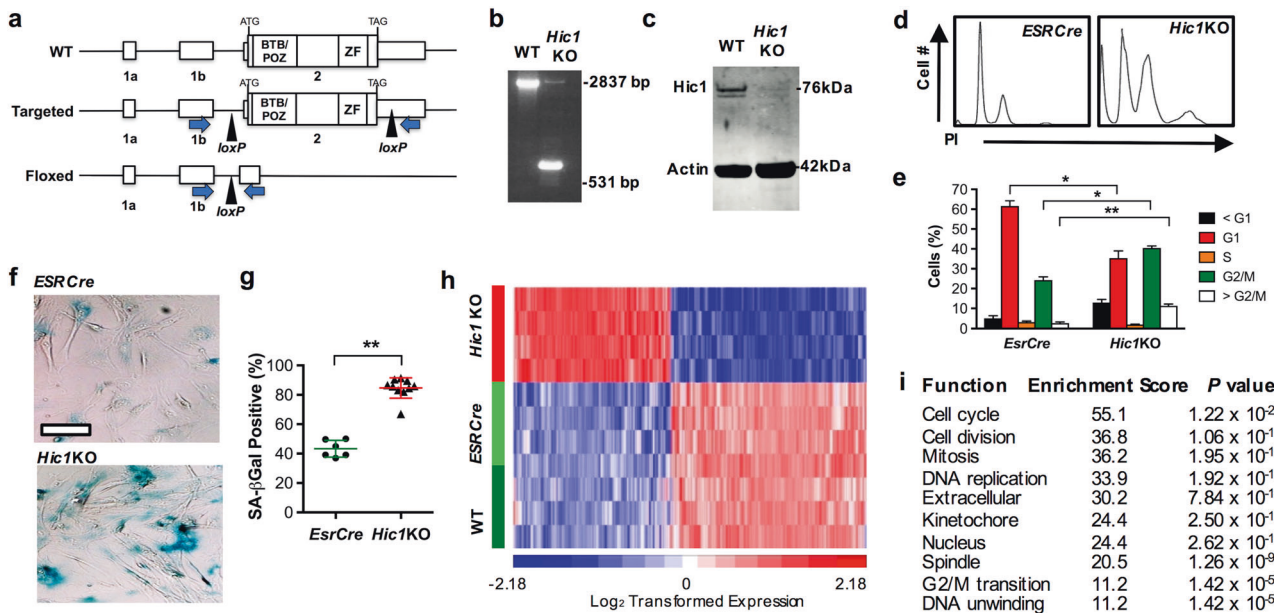


Fig. 1 Conditional deletion of *Hic1* in mouse embryonic fibroblasts (MEFs). Experiments in this Figure were analyzed by an unblinded observer unless otherwise stated. Female mice used in this study were housed under SPF conditions with a standard day/night cycle and fed ad libitum on a pure C57Bl6 background following approval by the Monash Animal Ethics Committee (MMCA/2012/23; MMCA/2012/24; MMCA/2013/26) in accordance with current National Health and Medical Research Council guidelines. All mice were obtained from Jackson Laboratories except for the conditional *Hic1^{lox/lox}* transgenic line, which was generated by Ozgene (Perth, WA, Australia). Genotyping was performed with Jackson Laboratory protocols except for the *Hic1^{lox/lox}* line which was genotyped using primers as follows: Fwd 5'-cgcagaccacgcactct-3', Rev 5'-cccaggctaaggcactaacag-3', 486 wt; 312 mutant. MEFs were generated and cultured as described [65]. **a** Targeting strategy, showing exons 1a, 1b and 2 and loxP sites in the wild type (WT), targeted and floxed locus following Cre-mediated excision. PCR primers to detect excision of exon 2 are shown as blue arrows. Primers: Fwd 5'-caactgtactgtgcatcc-3' and Rev 5'-cagctaaagtgggctcagg-3'. **b** Genomic PCR using the primers indicated in Fig. 1a. from wild type (WT) or *ESrCre-Hic1^{lox/lox}* (*Hic1KO*) MEFs treated with tamoxifen to induce Cre-mediated recombination. **c** Western blot analysis of Hic1 and Actin expression in MEF cell lysates from the same experiment shown in Fig. 1b. To generate the Hic1 antibody, full length human HIC1 was cloned into the pET-15b vector and soluble recombinant full length HIC1 protein. Antiserum against full length HIC1 protein was raised in rabbits by the Antibody

Facility at Flinders University of South Australia. Hic1 antibodies were purified from serum using a NAb Protein A Plus Spin Kit (Thermo Scientific, Waltham, MA, USA, #89978). Validation experiments relating to this antibody are shown in Supplementary Fig. S1. The Actin antibody was obtained from Abcam, Cambridge, UK (#abactn05). **d** Representative DNA histograms from *ESrCre* and *Hic1KO* MEFs 48 h following treatment with tamoxifen. **e** Quantitative analysis of the data shown in Fig. 1f. $n = 4$, mean + SEM, ** $P < 0.01$, * $P < 0.05$, one-way ANOVA with Bonferonni correction. Cell cycle analysis and sample size was performed as described [66, 67]. **f** Phase contrast photomicrographs of senescence-associated β-Galactosidase (β-Gal) staining in *ESrCre* or *ESrCre-Hic1^{lox/lox}* (*Hic1KO*) MEFs 5 days following tamoxifen treatment. Scale bar = 50 μm. Cells were stained and scored by an observed blinded to the MEF genotype as described [68]. **g** Quantitative assessment of β-Gal staining in the same experiment shown in Fig. 1h. $n = 5-10$, ** $P < 0.01$ unpaired *t*-test. **h** A heat map depicting differentially expressed genes from pre-immortal wild type (WT), *ESrCre* and *Hic1KO* MEFs 48 h following treatment with tamoxifen, performed by the Australia Genome Research Facility (Melbourne, VIC, Australia) using the MouseWG-6 v2.0 Expression BeadChip (Illumina, San Diego, CA, USA) as previously described [69]. Detailed bioinformatic methods are described in Supplementary Information. Array data are available through GEO, GSE104394. **i** Gene ontology analysis of differentially expressed genes in *Hic1KO* MEFs compared with WT and *ESrCre* MEFs 2 days following tamoxifen treatment

from *p53KO* MEFs developed with a longer latency period (Fig. 2b). No tumors developed from *ESrCre* MEFs

Gene expression profiling of immortalized *ESrCre*, *p53KO*, and *Hic1KO* MEFs revealed a highly divergent transcriptional signature (Fig. 2c, d; Supplementary Tables S3,4,5). When compared with *p53KO* cells, *Hic1KO* MEFs upregulated gene sets strongly associated with DNA synthesis, senescence, oxidative and nutrient stress (Fig. 2e). As expected, expression of *Cdkn1a* (which encodes p21) was markedly downregulated in *p53KO* cells while immortalization in response to deletion in *Hic1* was

associated with dramatic loss of *Cdkn1c* gene expression (which encodes p57) (Supplementary Table S5). Genomic and RT-PCR sequencing also showed that immortalized *Hic1KO* MEFs retained intact *Tp53* and *Cdkn2a* genes (data not shown), both of which are commonly inactivated in MEFs that spontaneously escape senescence [36]. To further define the status of *Tp53* in this model, we treated WT or immortalized *Hic1KO* MEFs with doxorubicin to induce DNA damage. As shown in Fig. 2f, this resulted in robust upregulation of *Tp53* and phosphorylated *Tp53* expression. Using a *Tp53*-responsive reporter system, we further showed

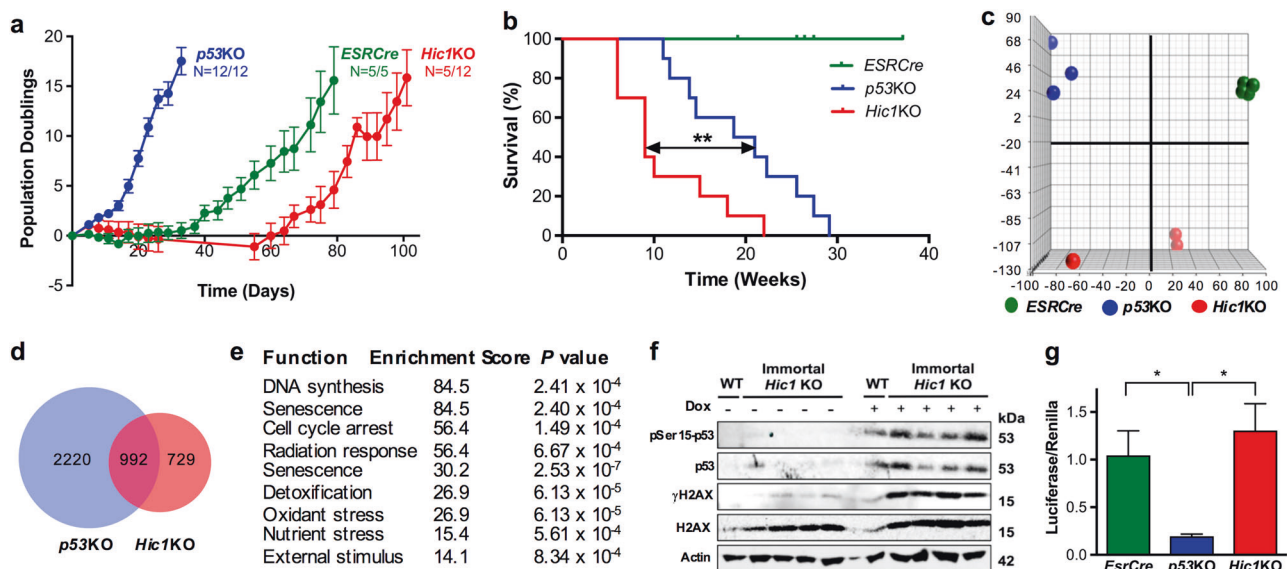


Fig. 2 Immortalization of MEFs lacking *Hic1* results in a phenotype distinct to MEFs lacking *p53*. **a** Growth of MEFs (shown as cumulative population doublings) following tamoxifen treatment using the 3T3 protocol [65]. Data shown as mean+SEM. Sample size was determined by the number of available immortalized MEF lines. Cell lines were checked for *Mycoplasma* and genotype every 6 months. **b** Kaplan–Meier survival analysis of athymic nude mice injected with 1×10^6 immortalized MEFs with the genotypes indicated. $**P < 0.005$, log-rank analysis. 1×10^6 MEFs were resuspended in $50 \mu\text{l}$ media+ $50 \mu\text{l}$ Matrigel and injected subcutaneously in the right flank and observed for 26 weeks, until the tumor reached 800 mm^3 measured by an observed blinded to the MEF genotype. **c** Principal component (PC) analysis of gene expression in immortalized MEFs generated from embryos with the genotypes indicated compared to control MEFs. Detailed bioinformatic methods are described in Supplementary Information. Array data are available through GEO, GSE104394. **d** A Venn diagram depicting differentially expressed genes in the

immortalized MEF lines shown in Fig. 1c when compared with control MEFs. **e** Gene ontology analysis of differentially expressed genes when comparing immortalized *p53KO* vs. *Hic1KO* MEFs. The analysis was performed by an observer with no *a priori* knowledge of the cellular phenotype. **f** Western blot analysis of lysates from wild type (WT) or *Hic1* KO MEFs showing the expression of p53 phosphorylated at serine 15 (pSer15-p53, Cell Signaling Technology, Danvers, MA, USA, #9284S), p53 (Santa Cruz Biotechnology, Dallas, TX, USA, sc-6243), phosphorylated- γ H2AX (γ H2AX, Novus Biologicals, Littleton, CO, USA #NB100-74435), total H2AX (Cell Signaling Technology, 2595 S) and Actin [66, 67]. Cells were treated with vehicle or doxorubicin (Dox; $1 \mu\text{M}$, 6 h). **g** Activity of a p53-responsive luciferase reporter (Qiagen, Hilden, Germany, #CCS-004L) in MEFs 24 h after treatment with doxorubicin, $1 \mu\text{M}$, for 6 h. $n = 4$ independent cell lines performed, each performed in triplicate, mean + SEM, $*P < 0.05$

that both *EsrCre* and *Hic1KO* MEFs were able to induce a p53-dependent transcriptional response when compared to *p53KO* MEFs (Fig. 2g).

Taken together, these data show that immortalization following the loss of *Hic1* occurs independent of *TP53*. Although we cannot exclude the possibility that attenuation of *TP53* function plays a role in maintenance of the immortalization phenotype in *Hic1KO* MEFs, the weight of evidence strongly suggests that a significant component of the tumor suppressive activity of *Hic1* in the context of tumor initiation outside the previously described *Hic1*-*TP53*-Sirt1 regulatory loop [28].

Loss of *Hic1* in MEFs leads to chromosomal instability

Chromosomal instability is a cardinal feature of tumors with defective HR, typified by cancers with mutations in *BRCA1* and *BRCA2* [37]. Considering the similarities between

Hic1KO and *Brcal* mutant MEFs, we asked whether loss of *Hic1* function in immortalized MEFs would result in chromosomal instability. Quantitative anaphase analysis of immortalized MEFs revealed largely normal chromosomal morphology in *EsrCre* MEFs, whereas multipolar spindle formation was the predominant defect in *p53KO* MEFs (Fig. 3a, b), in keeping with previous reports [38]. The prevalence of lagging chromosomes was similar across all genotypes. By contrast, mitoses in *Hic1KO* MEFs were characterized by frequent anaphase bridges (Fig. 3a, b), consistent with a defect in HR mediated repair of DSB [39].

We next analyzed the consequences of this ongoing chromosomal instability with karyotype analysis in each of the immortalized MEF lines. Both *EsrCre* and *p53KO* cell lines were near tetraploid, resembling the stable karyotype of NIH-3T3 cells, a well-characterized MEF line generated by spontaneous immortalization (Fig. 3e, f) [40]. In keeping with the degree of anaphase bridge formation, numerical and segmental aneuploidy with large numbers of marker

chromosomes was seen in *Hic1*KO MEFs (Fig. 3e, f). Histologic analysis of the MEF allograft tumors described in Fig. 2b showed that *Hic1*KO MEFs formed aggressive, pleomorphic sarcomas with some features of skeletal muscle differentiation resembling adult pleomorphic rhabdomyosarcoma (Fig. 3h). By contrast, *p53*KO MEFs form sarcomas more consistent with pediatric rhabdomyosarcoma, with a more regular nuclear morphology. Consistent with our in vitro findings, *Hic1*KO MEF nude mouse allograft tumors exhibited marked nuclear pleomorphism, as well as numerous anaphase bridges and multinucleated

giant cells (Fig. 3i). These histological findings are consistent with marked chromosomal instability [41–43].

Cooperation between inactivation of *Hic1* and oncogenic KRas in vivo

Our data suggest that loss of *Hic1* in the setting of the replication stress and impending senescence induced by culture of MEFs [44] can lead to chromosomal instability and spontaneous transformation. To test the functional importance of this observation in vivo, we made use of a

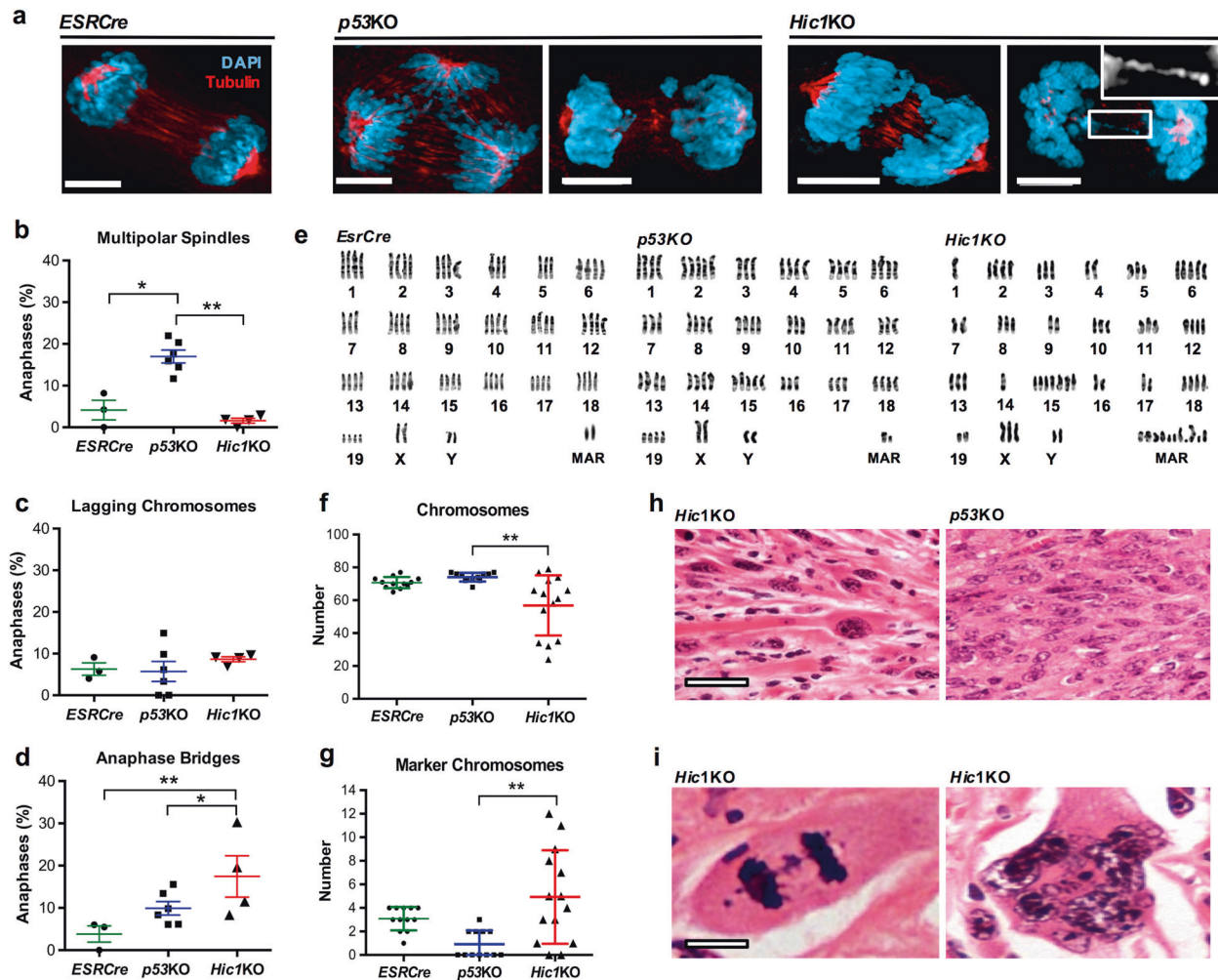


Fig. 3 Deletion of *Hic1* results in chromosomal instability. **a** Representative confocal photomicrographs showing anaphases in MEFs with the genotypes indicated. Cells were stained for tubulin (Red) and DNA (DAPI) (Blue) as described [66]. Scale bar = 5 μ m. Anaphases in cell culture were scored as described previously by an observer blinded to the MEF genotype [66]. **b–d** Quantitative analysis of aberrant anaphase events in MEFs with the genotypes from the same experiment shown in Fig. 1a, $n = 3$ (*ESRCre*), 6 (*p53KO*) and 4 (*Hic1KO*) cell lines, average of 55 anaphases per cell line. Mean \pm SEM. * $P < 0.05$; ** $P < 0.01$, one-way ANOVA with Bonferonni correction. Sample size was chosen by the number of available MEF lines. **e** Examples of karyotypes from immortalized MEFs with the

genotypes shown. Karyotyping was performed as previously described [70]. **f, g** Quantification of chromosome number and the number of marker chromosomes, $n = 4$ *ESRCre*, $n = 6$ *p53KO* and $n = 5$ *Hic1KO* cell lines, average of 15 metaphase cells per genotype. ** $P < 0.01$, one-way ANOVA with Bonferonni correction. **h** Representative photomicrographs of hematoxylin and eosin (H&E) stained sections from formalin-fixed, paraffin-embedded nude mouse allograft tumors with the genotypes indicated. Scale bar = 20 μ m. **i** Representative high-powered photomicrographs of H&E stained sections of *Hic1KO* nude mouse allograft tumors. Scale bar = 5 μ m. MAR marker chromosomes

conditional mouse model of lung adenocarcinoma in which an oncogenic mutant *KRas**G12D* allele is knocked into the endogenous *KRas* locus downstream of a *loxP-STOP-loxP* cassette (hereafter *KRas*) [45]. When treated with an inhaled recombinant adenovirus expressing Cre recombinase (Ad5Cre), these mice develop multiple lung adenocarcinomas within 6–8 weeks [46]. We chose this model based on (i) the ability of mutant *KRas* to trigger replication stress and senescence in the absence of a cooperating mutations in *Tp53* or p16 [47, 48]; (ii) the cooperating effect in this model on tumor progression due to combined deletion of *Tp53* [49]; (iii) the prevalence of HIC1 hypermethylation in human lung adenocarcinoma [50]; and (iv) the clinical significance of *HIC1* methylation in non-small cell lung cancer [18].

We crossed *KRas* and *Hic1*^{lox/lox} mice to generate wild type, *Hic1KO*, *KRas*, and *KRas* × *Hic1KO* experimental cohorts, and administered inhaled Ad5Cre at 6–8 weeks of age. Wild type and *Hic1KO* mice treated with Ad5Cre showed no abnormalities and did not develop lung lesions by 12 months of age (data not shown). As shown in Fig. 4a, *KRas* × *Hic1KO* mice treated with inhaled Ad5Cre had a shorter lifespan compared to *KRas* littermates, consistent with a reduced tumor latency. Consistent with this observation, quantitative histologic analysis showed a marked increase in tumor size (Fig. 4b, c). Immunohistochemical staining for Pancytokeratin, Surfactant Protein C and Thyroid Transcription Factor-1 confirmed the identity of the tumors as primary lung adenocarcinomas (Supplementary Fig. S1). Early *KRas* tumors retained *Hic1* expression, whereas this was lost in the *KRas* × *Hic1KO* tumors (Fig. 4e). *KRas* × *Hic1KO* tumors retained intact *Cdkn2a* and *Tp53* alleles (data not shown).

Tumors in the *KRas* animals displayed a well differentiated adenocarcinoma morphology consistent with previous reports [45]. In contrast, *KRas* × *Hic1KO* mice developed adenocarcinomas with prominent micropapillary and pleomorphic features (Fig. 4d), both of which are known to be associated with a poor prognosis in human lung cancer [51, 52]. To our knowledge, this is the first description of mouse model in which both these histologic features have been identified, and are distinct from tumors arising in *KRas*/p53 mutant animals [49]. In keeping with this aggressive phenotype, tumors from *KRas* × *Hic1KO* animals were more proliferative, evidenced by quantitative analysis of PcnA immunohistochemistry (Fig. 4f, g). Despite this proliferative advantage, *KRas* × *Hic1KO* tumors displayed prominent expression of nuclear γ H2AX (Fig. 4f, g), indicative of spontaneous DSB formation. Although we cannot exclude the possibility that deregulation of *Hic1* target genes may contribute to the micropapillary lung adenocarcinoma phenotype seen in *KRas* × *Hic1KO* mice, these data support our findings in the MEF model, and

demonstrate that loss of *Hic1* in the setting of oncogenic *KRas* activation in the adult airway epithelium leads to chromosomal instability and a distinct mouse lung adenocarcinoma phenotype.

A novel role for *Hic1* as a tumor suppressor

Using a conditional mutant mouse model, we have identified a new and unexpected function for *Hic1* as tumor suppressor by maintaining chromosomal stability in the setting of sustained DNA replication stress. Although our model may not be broadly applicable to the models in which the functions of *Hic1* have been described previously, our results do suggest that loss of *Hic1* function in the early phases of tumor initiation may have a major impact on the subsequent tumor phenotype. These data support the notion that the acquisition of chromosomal instability during the early phases of tumor evolution can have a major effect on tumor phenotype and genotype through deletion of tumor suppressors, amplification of oncogenes, and transcriptional deregulation [53–55]. Our results are also consistent with the idea that chromosomal instability can drive tumor evolution, as well as genomic, epigenetic and phenotypic heterogeneity [53–55].

Several lines of evidence support a potential role for *Hic1* in maintaining chromosomal stability independent of *Tp53*. In a human cell line model, Dehennaut et al. showed that *HIC1* promotes the response to DNA double strand breaks through an ATM-SIRT1-HDAC4 dependent mechanism [56]. Importantly, this was dependent on the interaction between HIC1 and MTA1, a component of the nucleosome remodeling and deacetylase (NuRD) complex. Interestingly, this complex is required for the effective DNA repair during S phase [57–59]. By contrast, Paget et al. recently showed that in response to repairable DNA damage, HIC1 was more important in mounting a transcriptional response to DSB than directly promoting DNA repair [60]. Although our data do not resolve this apparent contradiction, our findings are consistent with both papers in they support a role for *Hic1* in mediating DNA repair and/or in triggering cell death in response to DNA damage.

Interestingly, HIC1 is also known to interact with the tumor suppressor gene ARID1A [61], a component of the SWI/SNF chromatin remodeling complex that also has important roles in maintaining genome stability during DNA replication [62, 63]. This concept is strengthened by the observation that mouse embryonic stem cells lacking SWI/SNF protein Brg1 undergo cell cycle arrest associated with chromatin bridge formation and a defective decatenation checkpoint [64]. Taken together, these observations suggest that genome-wide interactions between *Hic1* and both the NuRD and SWI/SNF complexes may play a role in

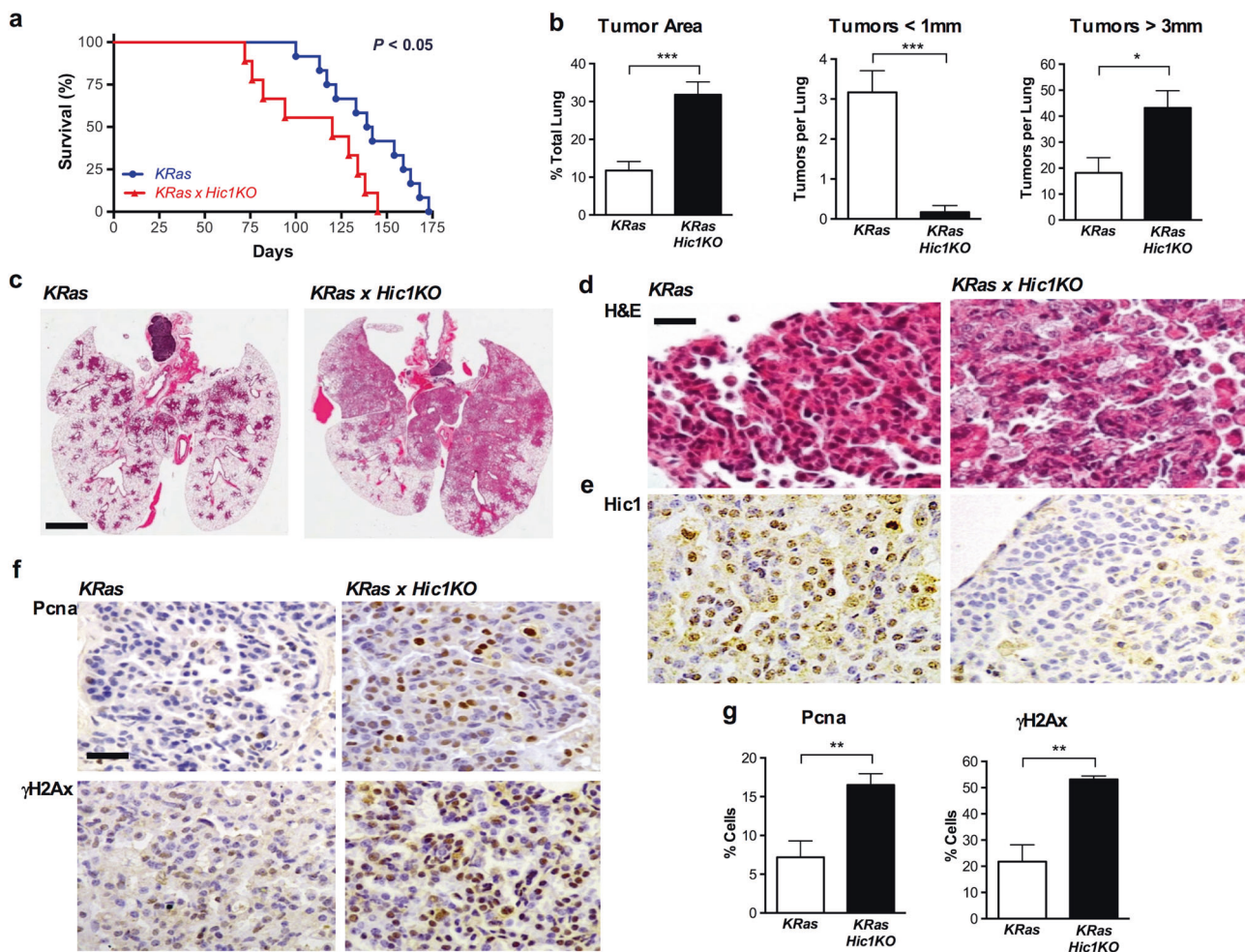


Fig. 4 Effects of *Hic1* deletion (*Hic1*KO) on the development of lung tumors induced by the conditional activation of an activating *KRAS*^{G12D} (*KRas*) mutant in the airway epithelium of adult mice. Mice from each genotype were anesthetized using Avertin at a dose of 0.5 mg/gram of body weight, and administered 5×10^8 PFU Ad5CMVCre virus (Viral Vector Core Facility, University of Iowa, Iowa City, IA) by intranasal inhalation at 8 weeks of age and observed for 9 months or until ethical endpoint. **a** Kaplan–Meier survival analysis of *KRas* and *KRas* \times *Hic1* KO mice following inhalation of adenoviral Cre recombinase. $n = 12$ (*KRas*) and 9 (*KRas* \times *Hic1* KO). Sample size was based on previous published studies [71]. **b** Quantitative analysis of lung tumor area and size in mice from the same experiment depicted in Fig. 4a. $n = 6$ per genotype, $***P < 0.001$, $*P < 0.05$, unpaired *t*-test. Mouse lungs were inflated with 10% buffered formalin and fixed overnight before paraffin embedding. For quantitation of tumor burden and number, sections were scanned using the Aperio Scanscope XT (Leica Biosystems, Buffalo Grove, IL, USA) and analysed using Aperio Imagescope

software by a blinded observer as described [71]. Sample size was chosen based on previous studies [71]. **c** Representative photomicrographs of hematoxylin and eosin (H&E) stained sections of lungs from the experiment depicted in Fig. 4a. Scale bar = 5 mm. **d** Representative high-powered photomicrographs of hematoxylin and eosin (H&E) stained sections of lungs from the same experiment. Scale bar = 20 μ m. **e** Representative photomicrographs of sections from the same tumors stained with immunoperoxidase (brown) for Hic1, and countersained with hematoxylin (blue). Immunohistochemistry was performed as described [71]. **f** Immunostaining for Proliferating cell nuclear antigen (PcnA, Dako, Troy, MI, #M087901-2) or phospho- γ H2AX (γ H2AX, Abcam, Cambridge, UK) in the same tumors shown in Fig. 4d. Immunohistochemistry and quantification of staining was performed as described [71]. Scale bar = 100 μ m. **g** Quantitative analysis of PcnA and γ H2AX staining from the same experiment depicted in Fig. 4f. $n = 5$ per genotype, 5 fields of view at 40 \times counted per animal. $**P < 0.01$, unpaired *t*-test

maintaining chromosomal instability during DNA replication.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no competing interests.

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