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Isoprenylcysteine carboxy methyltransferase (ICMT) is associated with tumor aggressiveness and its expression is controlled by the p53 tumor suppressor

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Running title: *p53 forms regulate ICMT expression in cancer*

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Abstract

Isoprenyl cysteine carboxy methyltransferase (ICMT) plays a key role in posttranslational regulation of prenylated proteins. On the basis of previous results, we hypothesized that the p53 pathway and ICMT expression may be linked in cancer cells. Here, we studied whether wt p53 and cancer-associated p53 point mutants regulate ICMT levels and whether ICMT overexpression affects tumor progression. Studying the effect of p53 variants on ICMT mRNA and protein levels in cancer cells, we found that wt p53 and p53 mutants differentially affect ICMT expression, indicating that p53 status influences ICMT levels in tumors. To investigate the underlying mechanisms, we constructed ICMT-luciferase reporters and found that wt p53 represses ICMT transcription. In contrast, p53 mutants showed a positive effect on ICMT expression. Promoter truncation analyses pinpointed the repressive effect of wt p53 to the -209 and -14 region, on the ICMT promoter, and chromatin immunoprecipitation assays indicated that wt p53 is recruited to this region. Instead, a different promoter region was identified as responsible for the mutant p53 effect. Studying the effect of ICMT overexpression on tumor-associated

phenotypes in vitro and in vivo, and analyzing breast and lung cancer databases, we identified a correlation between p53 status and ICMT expression in breast and lung cancers. Moreover, we observed that ICMT overexpression is correlated with negative clinical outcomes. Our work unveils a link between postprenylation protein processing and the p53 pathway, indicating that the functional interplay between wt and mutant p53 alters ICMT levels, thereby affecting tumor aggressiveness.

Introduction

ICMT is an enzyme involved in a complex post-translational modification process. The initial step involves the addition of farnesyl or geranylgeranyl isoprenoid to a cysteine residue close to the C-term of protein substrates (1), catalysed by farnesyl transferase or geranylgeranyl transferase I. The prenylated cysteine residue is usually part of a CAAX motif (C: cysteine; A: aliphatic amino acid; X: any amino acid), but other motifs such as CXC can also be targeted by prenyltransferases (2). Then, the terminal aminoacids following the prenylated cysteine are eliminated by a specific peptidase known as RCE1, at the endoplasmic reticulum (3). Finally, ICMT catalyses

methylation of the free carboxyl end on cysteine. This modification provides a hydrophobic uncharged C-terminus to the substrate protein that increases the interaction with biological membranes and/or modifies the ability to interact with protein partners (4). The existence of more than 200 CAAX proteins has been predicted based on sequence and structural analyses (5, 6). An intriguing aspect of prenylated proteins is that they are distributed among different families and are involved in a variety of biological functions (reviewed in (7)).

The identification of RAS family members as ICMT substrates reinforced the notion that protein prenylation may play a role in cancer (8, 9), as suggested by pioneering reports on the inhibitory effect of HMGCR inhibitors on cell proliferation (10–12). Supporting this hypothesis, genetic ablation of *ICMT* reduced KRAS-induced transformation of mouse embryo fibroblasts *in vitro* (13). Tissue specific deletion of *ICMT* in mice expressing mutant KRAS in myeloid cells and pneumocytes, attenuated myeloproliferative syndrome and reduced the areas of neoplastic lesions in the lungs (14). Supporting a role in RAS-driven tumorigenesis, genetic ablation of *ICMT* in breast cancer cell lines harbouring mutant RAS, reduced tumor formation in a xenograft model (15). In contrast, ICMT can also cooperate with tumor suppression, since its inactivation in pancreatic progenitor cells increased the number of KRAS-driven intraepithelial neoplasias and promoted the progression to pancreatic ductal adenocarcinoma (16). Some RHO GTPase family members are also modified by ICMT (17), providing other potential connections with oncogenic mechanisms. For example, the involvement of RHO family members on actin cytoskeleton remodelling and cell motility suggests that they may affect invasiveness and metastasis (18). ICMT inhibition reduced migration and invasion in MDA-MB-231 cells *in vitro* (19), concomitant with decreased RHOA and RAC1 activity. Likewise, a decrease in migration and *in vivo* invasion associated to RAB4A impaired function was observed in HT-1080 fibrosarcoma cells upon ICMT inhibition (20). Nevertheless, a complex scenario may be envisaged, since the initial view proposing that RHO GTPases play a pro-neoplastic role has been challenged by recent data from *in vivo* models and human tumors (reviewed in (21)). Furthermore, ICMT deregulation is

expected to exert complex effects on RHO GTPases since the action of ICMT on specific substrates may have different and even opposing consequences on subcellular localization and/or expression levels (22–24). This evidence indicates that ICMT cannot be considered a proto-oncogene under all circumstances and that several aspects of its biological role are still underexplored. In this context, characterizing the connection between ICMT function and specific oncogenic signalling circuits may help to understand its contribution to cancer.

Despite the growing interest on ICMT, little attention has been paid to the mechanisms that control its expression. Previous results from microarray analysis (25) suggested us that *ICMT* expression may be enhanced by mutant p53. The role of p53 as a tumor suppressor has been extensively documented by a large body of evidence, showing that it constitutes the central hub of a signalling pathway activated in response to stress signals (26). Accordingly, the presence of mutations in the p53 gene (*TP53*) is the most frequent genetic alteration in human cancer (27, 28), characterized by the conspicuous expression of point mutants that may acquire neomorphic activities (29). The presence of mutant p53 proteins may have different consequences on cell physiology (30). On the one hand, p53 point mutants may inhibit wt p53; on the other, they may also activate wt p53-independent mechanisms, through new capabilities conferred by the mutation. Compelling evidence from mouse models showed that the expression of p53 point mutants promotes the development of aggressive tumors (31). Nevertheless, the rationalization of the functional complexity of p53 mutants as well as their precise role in different cancer types remains a challenge.

In order to explore the existence of a link between the p53 pathway and post-prenylation processing we studied the effect of wt and p53 mutant forms on ICMT expression. We also analysed the consequences of altering ICMT levels on tumor phenotypes, and we studied the impact of ICMT expression in breast and lung cancer.

Results

Mutant and wt p53 exert opposing effects on ICMT expression. The presence of p53 point mutants was proposed to affect gene expression in tumor cells through different mechanisms. Previous results from microarray analysis on

MDA-MB-231 breast cancer cells (25), which endogenously express p53R280K and lack a functional wt *TP53* allele, indicated us that ICMT expression was reduced upon mutant p53 knock down, thus suggesting a positive regulation. To test this hypothesis, we first confirmed the effect of endogenous p53R280K knock down on ICMT mRNA steady state levels in independent experiments. Upon siRNA transfection in MDA-MB-231 cells, total RNA was extracted and qPCR was performed on cDNA samples. We found that knock down of endogenous mutant p53 reduced ICMT mRNA levels (Figure 1a). Accordingly, western blot analysis showed that ICMT protein levels were reduced upon p53R280K knock down in the same cell line. We performed a similar analysis on MDA-MB-231 cells where p53R280K expression was stably knocked down. Cells were transduced with retroviral plasmids expressing shRNAs that target two different regions on the p53 mRNA: the same region targeted by the p53 siRNA and a second region present in the 3' UTR (25). Our results confirmed that ICMT mRNA and protein levels were reduced upon p53R280K silencing with both shRNAs (Supplementary Figure 1a), thus indicating that the observed changes are not due to off-target effects. To further confirm our results, we analysed data from an independent GEO dataset, previously published by other authors (32). We found that *ICMT* expression was significantly reduced in MDA-MB-231 cells when p53R280K was knocked down, as expected (Supplementary Figure 1b). To understand whether other point mutants behave similarly, we concentrated on p53R273H, which is one of the most frequent p53 mutants in human cancer (33). A similar effect on ICMT mRNA and protein levels was observed when we knocked down endogenous p53R273H in breast adenocarcinoma MDA-MB-468 and colorectal adenocarcinoma HT29 cells (Figure 1b and c). These results are in agreement with the hypothesis that mutant p53 promotes *ICMT* expression. Taking into consideration the close functional interplay between mutant and wt p53 forms (30, 34), we decided to study the effect of wt p53 on ICMT expression. To understand if wt p53 may also affect ICMT mRNA steady state levels, we transfected H1299 p53 null cells with a plasmid expressing wt p53 and performed qRT-PCR. Expression of wt p53 significantly reduced ICMT mRNA levels compared to control cells transfected with empty vector (Figure 1d). In

addition, ICMT protein levels were reduced upon wt p53 transfection. Conversely, ICMT mRNA and protein levels increased upon expression of p53R280K (Figure 1d). A similar effect on ICMT protein levels was observed when we expressed other p53 point mutants (R273H or R175H) in H1299 cells (Supplementary Figure 1c). These results confirmed that other point mutants affect ICMT expression.

To further explore the regulation of ICMT expression, we analysed the effect of endogenous wt p53 stabilization on ICMT levels using MCF-7 breast cancer cell line. Cells were treated with nutlin-3, a specific inhibitor of the interaction between p53 and HDM2 ubiquitin ligase (35), and protein levels were analysed by western blot. As expected, wt p53 levels were increased upon treatment, and concomitantly, a reduction of ICMT levels was observed (Figure 1e). Similar results were obtained when we treated HCT116 p53^{+/+} colon carcinoma cells. Moreover, reconstitution of wt p53 expression in syngeneic HCT116 p53^{-/-} cells significantly reduced ICMT mRNA and protein levels (Figure 1f). These results confirmed the opposing effect of both p53 forms on ICMT levels.

To understand whether p53 forms affect *ICMT* transcription, we amplified a fragment of the ICMT promoter ranging from -2234 to +37 on MDA-MB-231 genomic DNA, and cloned it into pGL3-basic vector, in order to generate a reporter (pICMTluc). Luciferase assays were performed upon co-transfection of a plasmid expressing p53R280K with pICMTluc into H1299 p53 null cells. We found that p53R280K expression significantly enhanced reporter activity in the absence of wt p53 (Figure 2a and b). These results are in agreement with our previous observations and support the idea that mutant p53 cooperates with ICMT expression through the acquisition of wt p53-independent activities. Similar experiments were performed co-transfecting pICMTluc with plasmids expressing other p53 point mutants (R273H, R175H, R248W, R249S). We observed a significant enhancement of reporter activity in all cases (Figure 2a and b). In contrast, when we performed luciferase assays in H1299 cells, introducing the wt protein, we found that the activity of the promoter was markedly repressed (Figure 2a and b), indicating that *ICMT* transcription is negatively regulated by the p53 pathway. We also analysed whether wt p53 induction by doxorubicin treatment may affect

ICMT promoter activity. HCT116 p53^{+/+} or HCT116 p53^{-/-} cells were transfected with pICMTluc and pCMV-β-galactosidase as transfection control, and upon 24 h treatment, luciferase activity was determined. We found that reporter activity was significantly reduced upon induction of wt p53 in HCT116 p53^{+/+} cells, but unaffected in HCT116 p53^{-/-} cells (Figure 2c;). These results showed that wt p53 was required for ICMT promoter repression upon induction.

Considering that wt and mutant p53 forms are expected to coexist, at least transiently, during tumor progression, we wondered if the interplay between both p53 forms affects ICMT expression. We co-transfected p53R280K and wt p53 with pICMTluc in H1299 cells and measured reporter activity. We found that the presence of p53R280K almost completely counteracted promoter repression by wt p53 (Figure 2d). These results suggest that the acquisition of a missense mutation on *TP53* would exert a profound effect on ICMT expression by inactivating one wt allele but also because of the dominant negative effect on the remaining wt protein.

In order to identify the region responsible for the wt p53 repressive effect, we generated different reporters containing deletions of the ICMT promoter (Figure 3a). Luciferase assays were performed co-transfecting each reporter with a plasmid expressing wt p53. We found that the repressive effect was maintained on the fragment between positions -209 to +37, but it was almost completely absent on the fragment ranging from -14 to +37 (Figure 3b), indicating that the region between positions -209 and -14 is required for repression by wt p53. Accordingly, when we cloned the -209 -14 fragment into pGL3-Promoter vector, upstream of the SV40 promoter that drives luciferase transcription, we found that the activity was significantly reduced, compared to control cells (Figure 3c). Instead, wt p53 showed no effect on empty pGL3-Promoter vector, demonstrating that the identified promoter fragment is able to drive wt p53-dependent transcriptional repression. To confirm that this region is responsible for the wt p53 repressive effect in the context of the ICMT promoter, we generated a reporter containing the -2234 +37 promoter fragment bearing a deletion between positions -209 and -14 (pICMTlucΔ(-209-14)). As expected, our results showed that the absence of the identified region completely abolished promoter repression by wt p53 (Figure 3d). To understand if wt p53 may act

directly on the ICMT promoter, we performed chromatin immunoprecipitation experiments. H1299 cells were transfected with a plasmid expressing wt p53 and pICMTluc, and the protein was immunoprecipitated using an anti p53 antibody. We found that a 102 bp fragment between positions -66 and +36 on the ICMT promoter could be amplified on the immunoprecipitated DNA from cells expressing wt p53 (Figure 3e), but not from cells lacking wt p53, confirming the recruitment of the protein on the ICMT promoter.

Next, we mapped the region involved in the mutant p53 effect. We performed luciferase assays with the same reporters used for wt p53. A clear reduction on promoter activation by p53R280K was found using all the subsequent reporter deletions, comparing with the -2234 +37 promoter fragment, indicating that the effect of mutant p53 depends on the region between -2234 and -1130 (Figure 4a). Moreover, p53R280K was able to enhance promoter activity also on pICMTlucΔ(-209-14) reporter, showing that the region between -209 and -14 is not involved in this effect (Figure 4b). In addition, by performing ChIP assays in H1299 cells transfected with p53R280K, we were able to amplify a fragment between positions -2178 and -2071 on the ICMT promoter (ICMT up) upon immunoprecipitation with an anti p53 antibody (Figure 4c). In contrast, we could not amplify the fragment between positions -66 and +36 (ICMT down) on mutant p53 bound DNA (Figure 4c). Therefore, our results show that p53R280K is recruited on the ICMT promoter on a different region than wt p53, indicating that each protein regulate promoter activity by different mechanisms.

ICMT overexpression enhances tumor phenotypes

Collectively, our results showed that the ICMT promoter is under negative regulation by the p53 pathway. Conversely, tumor-associated p53 mutants counteracted this repressive effect, suggesting that the acquisition of missense mutations on *TP53* may further cooperate to increase ICMT expression. On this basis, we hypothesized that an uncontrolled increase in ICMT levels may cooperate with pro-oncogenic processes. Therefore, we decided to study the consequences of increasing ICMT levels on tumor-associated phenotypes. To this end, we generated pLPC-ICMT-GFP retroviral construct, containing the ICMT coding sequence fused to the

EGFP N-terminus. H1299 cells were transduced with retroviral particles containing pLPC-ICMT-GFP or pLPC-GFP as control. ICMT-GFP expression was confirmed by western blot and fluorescence microscopy (Supplementary Figure 2a and b). We observed that ICMT-GFP localized in a discrete cytoplasmic area in close association with the nucleus, in agreement with the localization in the endoplasmic reticulum described for this enzyme (36). In contrast, GFP was uniformly distributed in the cytoplasm of control cells. We first analysed the effect of ICMT on cell proliferation *in vitro* (Supplementary Figure 2c), but no significant differences in the proliferation rate between ICMT overexpressing cells and control cells were found.

To understand if high ICMT levels may promote clonogenic capacity *in vitro* we performed colony formation assays. H1299 cells stably expressing pLPC-ICMT-GFP or pLPC-GFP were plated at low density and incubated to allow clonal growth. Our results showed that cells overexpressing ICMT developed a significantly larger number of colonies compared to control cells (Figure 5a). These results suggest that high ICMT levels may confer an advantage to survive and proliferate under restrictive conditions, such as those imposed by low density culture. Accordingly, treatment of cells with the ICMT inhibitor Cysmethynil reduced the clonogenic potential of H1299 and MDA-MB-468 breast cancer cells in similar colony formation assays (Supplementary Figure 2d). To further explore this aspect, we studied the ability of ICMT overexpressing cells to develop tumors *in vivo* (Figure 5b). H1299 cells stably expressing ICMT-GFP, or GFP as control, were injected subcutaneously into nude mice and tumor development was monitored periodically. We found that 80 % of mice injected with cells expressing ICMT-GFP developed tumor masses (8 / 10). In contrast, tumors were found in only 33.3 % of mice injected with control cells (3 / 9). Moreover, tumors arising from ICMT-GFP expressing cells developed significantly earlier compared to controls. We also observed that palpable masses in control mice were smaller than those in mice injected with ICMT-GFP expressing cells. In summary, our results showed that high ICMT levels enhanced the tumorigenic potential of H1299 cells *in vivo*.

Next, we wondered which are the mechanisms activated by ICMT overexpression. Some studies were focused on particular substrates such as RAS

and RHO GTPases. Evidence from models of Ras-induced tumorigenesis have shown that ERK phosphorylation is reduced upon *ICMT* genetic inactivation (14). Therefore, in order to understand whether ICMT may have a similar effect in H1299 cells we performed western blot studies with a p-ERK antibody. We found that phosphorylated ERK is readily detectable, suggesting a high level of this modification. This observation may be explained by the presence of a constitutively active NRAS mutant form in this cell line. Neither ICMT knock down nor Cysmethynil treatment affected ERK phosphorylation, which, on the contrary, was clearly reduced upon treatment with MEK inhibitor U0126 (Supplementary Figure 2e). Therefore, our results strongly suggest that the pro-oncogenic effects of ICMT in H1299 cells do not involve ERK activation by RAS. To further explore the mechanism affected by ICMT, we studied changes on the cytoskeleton, in view of the relevance of RHO GTPases as regulators of actin polymerization. Cells were transfected with pLPC-ICMT-GFP or pLPC-GFP, plated on matrigel-covered glass and probed with fluorophore-conjugated phalloidin. Actin distribution was analysed by fluorescence microscopy in GFP-positive cells. Upon transfection of ICMT-GFP, a large proportion of cells showed a rounded morphology with accumulation of actin near the plasma membrane, suggesting filament bundling. In contrast, the proportion of control cells showing this morphology was markedly reduced (Figure 5c). These results showed that ICMT overexpression altered actin distribution in H1299 cells.

Interplay between ICMT and p53 status in Breast and Lung cancer. Our results from *in vitro* and *in vivo* experiments suggest that ICMT overexpression can cooperate to force mechanisms of aggressiveness, and consequently, its expression should be kept under strict control by proteins with tumor suppressive functions, like wt p53. Conversely, the acquisition of mutations in *TP53* may cooperate with tumor progression by promoting ICMT overexpression. To explore the clinical relevance of our findings we analysed breast cancer public databases. First, we wondered if p53 status affects ICMT expression. We analysed microarray data from 25 independent public databases searching for correlations between ICMT mRNA levels and p53 function

(BC compendium: 3661 cases). Since *TP53* mutation status was not available in this compendium, we analysed the expression of the p53 gene signature, in order to discriminate between cases with wt p53 and those with p53 alterations. The wt p53 signature was defined based on the expression profile of human tumors with known p53 status, and was previously shown to be strongly correlated with the presence of wt p53 alleles (37). Conversely, the mutant p53 signature was correlated with the presence of a mutant *TP53* gene, including cases with different types of mutations (deletions, nonsense, missense). We found that cases with a high mutant p53 signature score showed relatively higher ICMT mRNA levels. Accordingly, cases with a high wt p53 signature score showed significantly lower levels of ICMT mRNA (Figure 6a). These results strongly suggest that the presence of wt p53 in tumors correlates with low ICMT expression, in line with our results from experimental models. Taking into account that most cases with *TP53* mutation are likely to express p53 point mutants, our results also suggest that mutant p53 favours ICMT overexpression in tumors. High p53 protein levels in tumors are strongly correlated with the presence of p53 mutant forms (38). Therefore, we analysed ICMT mRNA levels in cases where data of p53 expression, assessed by immune histochemistry (IHC), was available (596 cases). Supporting our observations, ICMT mRNA levels significantly increased in cases with high p53 protein levels (Figure 6b).

Next, we extended our analysis to determine if similar correlations may be observed in lung cancer. To this end, we classified cases from the TCGA lung adenocarcinoma dataset (LUAD: 516 cases) according to the expression of the p53 signature, as explained for the BC compendium. We found significantly higher ICMT mRNA levels in cases with a high mutant p53 signature score as compared to cases with a low mutant p53 signature score (Figure 6c). Accordingly, the mean standardized level of ICMT expression was reduced by more than two-fold in cases with a high wt p53 signature score (Supplementary Figure 3). To further explore the correlation between ICMT expression and the p53 pathway in lung cancer, we analysed mRNA levels in cases with *TP53* mutations, assessed by whole exome sequencing (WES), since p53 IHC data is not available in this dataset. In support to our

hypothesis, we found that ICMT mRNA levels were significantly higher in cases bearing *TP53* mutations, comparing with wt p53 cases (Figure 6d).

Finally, we wondered if ICMT expression may correlate with clinical outcome. We found that cases with high ICMT mRNA levels in the BC compendium showed a significant decrease in metastasis-free survival (Figure 7a), suggesting that ICMT overexpression cooperates with metastasis development in breast cancer. When we stratified cases considering also p53 expression levels determined by IHC, we found that cases with low p53 expression (*i.e.* correlated with wt p53 status) and low ICMT mRNA levels showed a significantly increased metastasis-free survival compared to the other groups (Figure 7b). These results suggest that the metastasis promoting effect of ICMT is stronger in tumors retaining wt p53. Likewise, we found a significant correlation between high ICMT expression levels and a decreased overall survival in the lung cancer dataset (Figure 7c). A similar tendency as that observed in the BC compendium was found when we stratified cases considering p53 expression levels (Figure 7d). Collectively, our results support the idea that ICMT overexpression is associated to p53 pathway alteration and promotes tumor aggressiveness in breast and lung cancer.

Discussion

Protein prenylation is emerging as a critical post-translational modification that affects different aspects of cell physiology. Recently, exciting evidence proposed that altered prenylation or post-prenylation processing may cooperate with pathologies such as chronic inflammation, cancer, progeria and neurological disorders (7). However, the underlying mechanisms are not completely understood. The existence of three modification steps makes the study of protein prenylation and its biological consequences a challenging task, but also provides additional opportunities to manipulate the process (7). Inhibition of farnesyl transferase was proposed as a therapeutic strategy in cancer; however, the molecules tested in clinical trials showed a limited response. A possible explanation to this disappointing performance may be alternative prenylation by geranylgeranyl transferase I. Targeting post-prenylation processing offers the advantage that both RCE1 and ICMT can act on either farnesylated or geranylgeranylated substrates.

Studies on RCE1 showed relatively modest results and possible adverse effects including cardiomyopathy and retinopathy (7). In contrast, encouraging results for ICMT inactivation or inhibition have been observed in some experimental models. Therefore, a profound knowledge of the alteration of ICMT function in tumors is necessary to exploit its potential as a therapeutic target.

Studies in mice suggested that ICMT is differentially expressed, showing lower mRNA levels in skeletal muscle compared to brain and liver (39). Besides, a reduction in ICMT mRNA levels by binding of miR100 was observed in hepatocarcinoma cell lines (40). Nevertheless, to our knowledge, there are no further studies on ICMT expression and, in particular, on transcriptional regulation. In this work, we showed that the ICMT promoter is under regulation by p53 forms, including tumor-associated p53 point mutants, suggesting a complex interplay that may affect cell physiology. Our results show for the first time that *ICMT* is a target for transcriptional repression by wt p53. The effects exerted by wt p53 on gene expression are complex and may be influenced by cell context and the nature of the activating signals. Nevertheless, several independent studies have firmly established that wt p53 not only upregulates but also downregulates specific target genes (41). Different models were proposed to explain repression by wt p53, including direct and indirect mechanisms. We identified the region between -209 and -14 as responsible for the observed effect. Moreover, we found that wt p53 is recruited to the ICMT promoter in a region encompassing this fragment, strongly suggesting that the mechanism of repression involves the action of wt p53 as part of a regulatory complex on chromatin. *In silico* analysis of the identified promoter region failed to identify a p53 Response Element, even considering a modified consensus proposed to account for the deviations found in promoters of repressed target genes (42). Thus, we speculate that recruitment may involve the interaction with other proteins present in the promoter, although we cannot exclude binding to a highly divergent site.

In contrast, we showed that several p53 point mutants enhance ICMT expression, suggesting that overexpression of this enzyme may be related to mutant p53 oncogenic function. Our evidence also shows that this effect is associated to a gain-

of-function mechanism, since the enhancement of reporter activity and ICMT protein levels in H1299 cells is completely independent from wt p53. Moreover, our results showing that the effect of p53R280K was independent of the -209 -14 region and that the mutant protein was recruited on a different region on the promoter, indicate that wt and mutant p53 act through different mechanisms. In addition, co-expression with p53R280K eliminated the repressive effect of wt p53, showing a dominant negative effect. Thus, our results imply that the acquisition of missense mutations on *TP53* may cooperate to increase ICMT expression by complementary mechanisms. On the one hand, the repressive function of wt p53 may be lost upon mutation of one *TP53* allele and inhibition of the remaining wt protein by mutant p53. On the other hand, point mutants may activate wt p53-independent mechanisms.

Our findings suggest that ICMT expression should be strictly regulated in physiological conditions while alterations acquired during tumorigenesis, leading to functional inactivation of wt p53, would induce ICMT expression. In this context, such an increase in ICMT levels would be expected to cooperate with tumor progression. Supporting this idea, we show for the first time that ICMT overexpression enhances clonogenicity *in vitro* as well as tumorigenic potential *in vivo*. Some studies have described the effects of ICMT inhibition or silencing, however the effects of its overexpression have been poorly studied. We provide original evidence showing that ICMT overexpression enhances tumor-associated phenotypes in Non Small Cell Lung Carcinoma H1299 cells, suggesting that its deregulation may be relevant in this cancer type. Our results showed that the actin cytoskeleton is affected by ICMT overexpression. Considering the key role played by RHO GTPases as regulators of actin polymerization, it is likely that their activity may be affected by changes on ICMT levels. Individual overexpression of RHOA, RAC1 or CDC42 in the same conditions did not recapitulate the effect caused by ICMT (data not shown). Therefore, our results failed to identify a particular RHO GTPase as responsible for the observed effect. Alternatively, the alteration of actin cytoskeleton may be explained by the simultaneous action on several RHO GTPases.

Our analysis of public databases provides support to the idea that wt and mutant p53 exert opposite effects on ICMT expression in breast cancer,

showing that tumors classified as wt p53, are correlated with lower ICMT mRNA levels. Conversely, tumors classified as mutant p53 showed significantly higher ICMT mRNA levels. In addition, this hypothesis is further supported by our analysis based on p53 expression. Although p53 levels cannot be considered as a direct proof of p53 mutation, there is a strong association between p53 mutation and p53 overexpression in tumors (38). Our results showed a marked correlation between tumors with high ICMT mRNA levels and p53 overexpression. Considering that missense mutations are the most frequent genetic alterations on *TP53*, this evidence is in line with our *in vitro* results showing that p53 point mutants enhance ICMT expression. A similar correlation between ICMT mRNA levels and p53 status was observed in the lung cancer dataset, suggesting that the effect of the p53 pathway on ICMT expression is not restricted to a specific tumor type.

In agreement with our results from experimental models, ICMT overexpression showed a significant correlation with poor prognosis in the breast and lung cancer datasets analysed. A more detailed analysis of the BC compendium indicated that cases with low p53 and low ICMT expression displayed a significantly increased metastasis-free survival compared to all other groups. According to the criteria used in this classification, the group with low p53 expression is expected to include most of the wt p53 cases and all the p53 null cases. Consequently, our results suggest that ICMT overexpression in tumors that do not express mutant p53 forms (*ie.* wt or null) would have a stronger effect on metastasis development, compared to cases expressing p53 mutants. On this basis, it is possible to hypothesize that preventing ICMT overexpression, or inhibiting its function, in the low p53 expression group would increase survival. These results also suggest that therapies based on ICMT inhibition may be particularly efficient in patients with wt p53, which represent more than 70 % of breast cancer cases.

Previous evidence has shown that enhanced protein geranylgeranylation cooperates with tumor aggressiveness in breast cancer and that p53 point mutants promotes this effect by altering the mevalonate pathway (43, 44). ICMT overexpression may recapitulate some of the effects of mevalonate pathway alteration by affecting the function of geranylgeranylated

proteins. In this context, mutant p53 tumors may be less dependent on ICMT overexpression since they have already developed a mechanism to alter the function of proteins modified by geranylgeranylation. This partially overlapping effect may explain why ICMT overexpression exerted a more marked effect on the low p53 expression group (enriched in wt p53 cases) of the BC compendium (Figure 7b). Furthermore, expression of p53 point mutants are also predicted to activate other mechanisms of tumor aggressiveness which will be absent in wt or null p53 cases (30). Therefore, mutant p53-activated mechanisms would provide additional driving forces to foster tumor progression in cases with low ICMT levels. This could help to understand why ICMT expression did not show a significant difference in survival among cases in the high p53 expression group, (enriched in mutant p53 cases, Figure 7b).

In summary, our results unveil a connection between the p53 pathway and the prenylated protein network. We propose that ICMT expression is repressed by wt p53. Alteration of this regulation during tumor progression would impact on ICMT levels, which in turn would modify the action of prenylated proteins. Our findings reveal a mechanism through which tumor cells could manipulate the regulation of prenylated proteins in order to foster mechanisms of aggressiveness. Moreover, our findings also contribute to understand the clinical relevance of ICMT overexpression in breast and lung cancer, and suggest that therapeutic strategies based on ICMT inhibition may be particularly useful in wt p53 cases.

Experimental procedures

Cell culture. MDA-MB-231, MDA-MB-468, MCF-7, HT29, HEK293-GP, HCT116 p53^{+/+} and HCT116 p53^{-/-} were cultured in DMEM Medium supplemented with 10% fetal bovine serum and 100 U/ml penicillin and streptomycin (Invitrogen). H1299 cells were cultured in RPMI 1640 medium supplemented with 10% fetal bovine serum and 100 U/ml penicillin and streptomycin (Invitrogen). Cell lines were purchased from ATCC and authenticity was documented by standard STR analysis. Cells were cultured in a humidified incubator at 37°C with 5% CO₂ and tested periodically for Mycoplasma by DAPI staining and PCR.

Cell transfection and Retroviral Transduction. DNA and siRNA transfection was performed with Lipofectamine 2000 (Invitrogen) according to manufacturer's instructions. The following siRNAs sequences were used: sip53 targeting human *TP53* (GACUCCAGUGGUAUACUAC), siLacZ targeting LacZ gene from *Escherichia coli* (GUGACCAGCGAAUACCUGU) (25), siICMT (SMART pool M-005209-01-0005, Dharmacon). Stable genetic manipulation was performed by transduction with retrovirus-based plasmids as previously described (25). The following shRNAs were used for stable knock down (25): shp53 (GACUCCAGUGGUAUACUAC), shp53 3'UTR (GGUGAACCUUAGUACCUGU) and shLacZ (GUGACCAGCGAAUACCUGU).

Gene expression analysis. Total RNA was extracted using Trizol (Invitrogen) and subjected to DNase-I (Promega) treatment. RNA was retro-transcribed using M-MLV retrotranscriptase (Promega). Real-time PCR was performed using SYBR Green PCR master mix (Byodinamics) according to the following conditions: 2 min at 95 °C for one cycle; and 30 s at 95 °C, 20 s at 60 °C, 30 s at 72 °C for 40 cycles. Results were analyzed using the comparative $\Delta\Delta C_t$ method. Values were normalized to *GAPDH* expression. The following Real Time PCR primers were used: ICMTqPfw), ICMTqPrv), *GAPDH*fw, *GAPDH*rv, ICMTPrtfw-ChIP, ICMTPrtrv-ChIP, ICMTPrtfw-ChIPup, ICMTPrtrv-ChIPup (Supplementary Table 1).

Plasmids. Plasmid DNA was prepared using Wizard DNA Purification Kit (Promega). For wt and mutant p53 transient expression pCDNA3-p53 (45), pCDNA3-p53R280K (25), pCDNA3-p53R273H, pCDNA3-p53R175H, pCDNA3-p53R248W, (25) plasmids were used. pCDNA3-p53R249S was generated by site directed mutagenesis on pCDNA3-p53. pLPC-ICMT-GFP was constructed using pLPC-GFP vector (46). ICMT coding sequence was amplified by PCR on cDNA from H1299 cells using ICMTupLfw and ICMTpLRv. To generate pICMTluc reporter a fragment spanning from -2234 to +37 on the ICMT promoter was amplified by PCR on genomic DNA from MDA-MB-231 cells using ICMP2fw and ICMP1rv as primers and cloned into the pGL3-basic vector. This construct was used as a PCR template to generate a series of 5'-terminally truncated ICMT promoter fragments;

ICMTluc1000 (primers: ICMPMfw and ICMP1rv), ICMTluc500 (primers: ICMTQSacIfw and ICMP1rv), ICMTluc200 (primers: ICMT200SacIfw and ICMP1rv), ICMTluc50 (primers: ICMT50SacIfw and ICMP1rv). Each fragment was ligated into pGL3 basic vector. pICMTluc Δ (-209-14) was generated by overlap extension PCR (OE-PCR) using the following primer pairs: ICMP2fw/ICMTPrv (upstream fragment), and ICMTPrdfw/ICMP1rv (downstream fragment). Fragments were annealed and used as template to amplify a 2077 bp fragment with ICMP2fw and ICMP1rv primers. The fragment was cloned into pGL3vector. To generate pGL3P-ICMTluc200-50 reporter a fragment including the region between positions -209 and -14 on the ICMT promoter was amplified by PCR using pICMTluc as a template (primers: ICMT200KpnIfw and ICMT50upSacIrv) and cloned into pGL3-promoter vector (primer sequences are shown in Supplementary Table 1).

Luciferase Reporter Assay. H1299 and HCT116 cells were co-transfected with the indicated plasmids and pCMV- β -galactosidase (Promega) as a control of transfection efficiency, using Lipofectamine 2000 (Invitrogen). Transfected cells were harvested in Passive Lysis Buffer 1X (Promega). Luciferase activity was measured using Luciferase Assay Reagent (Promega) in a Multi-Mode Microplate Reader (Synergy™ 2, BioTek, USA). All experiments were repeated at least three times. The values were normalized relative to β -galactosidase activity. When indicated HCT116 cells were treated with 0,5 μ M Doxorubicin (Sigma) for 16 hs.

Chromatin Immunoprecipitation (chIP) Assay. ChIP assays were performed as previously described (25). Cells were transfected with pCDNA3-wtp53, pCDNA3-p53R280K or pCDNA3 as a control, and pICMTluc. Chromatin was sonicated to 500-800 bp average fragment size and pre-cleared for 1 h at 4°C with protein A-Sepharose (GE Healthcare). Chromatin was immune-precipitated with p53 DO1 (Santa Cruz). Co-immunoprecipitated DNA was analyzed by Real Time PCR. Promoter occupancy was calculated as percent of input chromatin using the $\Delta\Delta C_t$ method.

Colony formation assay. H1299 cells stably expressing ICMT-GFP or GFP as a control were

generated by retroviral transduction. Cells were plated at low density in 60 mm plates and cultured for 15 days to allow colony formation. Colonies were stained with Giemsa solution (Biopur diagnostics) and counted. To evaluate the effect of Cysmethynil (Cayman Chemical), H1299 or MDA-MB-468 cells were plated at low density in 60 mm plates and treated with 30 μ M Cysmethynil. For treatments, a stock solution of 13 mM Cysmethynil in DMSO was diluted in culture medium and the corresponding dilution of DMSO was used as control.

Western blotting and antibodies. Western blot was performed as previously described (25). As primary antibodies anti-GFP Ab290 (Abcam), anti-p53 DO-1 (Santa Cruz Biotechnology), anti-ICMT (Proteintech, 51001-2-AP), anti-actin (Sigma, A2066), anti-GAPDH G-9 (Santa Cruz Biotechnology), ERK C-9 (Santa Cruz Biotechnology) and p-ERK (Cell Signaling, 91015) were used. HRP-conjugated anti-rabbit (Jackson, 111-035-003) and HRP-conjugated anti-mouse (Jackson, 115-035-003) antibodies were used as secondary antibodies. Chemiluminescence was detected using Amersham ECL Prime Western Blotting Detection Reagent (GE Healthcare). For wt p53 stabilization MCF7 or HCT116 p53^{+/+} cells were treated with 10 μ M Nutlin-3 (Sigma) for 48 hs.

In vivo tumor formation Procedures involving animals conformed to institutional guidelines that comply with international laws and policies (The Council For International Organization Of Animal Sciences, (CIOMS) and The International Council for Laboratory Animal Science (ICLAS)). All experimental protocols were approved by the Animal Ethics Committee of the National University of Rosario (CICUAL-FBioyF). Six to eight-week-old female nude mice were obtained from the Animal facility of University of La Plata, Argentina. Animals were fed with commercial chow and water *ad libitum* and maintained in a 12 h light/dark cycle. Mice were randomly divided into 2 groups; group I: Control (n = 9), was injected with H1299 cells stably expressing GFP and group II: ICMT (n = 10) was injected with H1299 cells stably expressing ICMT. Cells were diluted 1:1 in Matrigel (Corning) and injected subcutaneously (1x10⁶/mouse). Palpable masses were measured twice a week with a caliper to determine major (D) and minor (d) diameters,

and the volume calculated using the ellipsoidal formula $V = \pi/6 \cdot D \cdot d^2$.

F-actin staining. H1299 cells were transfected with pLPC-GFP or pLPC-ICMT-GFP and 16 h later, plated in coverslips pre-coated with 1:100 Matrigel (Corning). After 24 h, cells were fixed and stained with 1:200 fluorescent phalloidin (Life Technologies). In average, 25 photos were taken per condition and the experiment was performed three times. Rounded cells with strong F-actin signal in proximity of the plasma membrane were counted over total cells.

Cell proliferation. H1299 cells were seeded at low density (5 x 10⁴) on 35 mm culture plates and incubated in RPMI medium supplemented with 10% FBS. Cell number was determined at different time points using a Neubauer chamber.

Collection and processing of gene expression data. Breast cancer: We started from a collection of 4,640 samples from 27 major data sets comprising microarray data of breast cancer samples annotated with histological tumor grade and clinical outcome. All data were measured on Affymetrix arrays and have been downloaded from NCBI Gene Expression Omnibus (GEO, <http://www.ncbi.nlm.nih.gov/geo/>) and EMBL-EBI ArrayExpress (<http://www.ebi.ac.uk/arrayexpress/>). Prior to analysis, we re-organized all datasets eliminating duplicate samples and re-naming each original set after the medical center where patients were recruited. Briefly, the datasets have been modified as described in (47). Lung adenocarcinoma: Gene expression RSEM (RNA-Seq by Expectation-Maximization) level 3 normalized data, TP53 mutations, and clinical information for n=516 samples of the TCGA lung adenocarcinoma (LUAD) dataset were downloaded from the GDAC Firehose. MDA-MB-231 cancer cell lines: Raw gene expression data (.CEL files) for control and mutant-p53 depleted MDA-MB-231 cells were downloaded from NCBI Gene Expression Omnibus GSE14491. Probe level signals were converted to expression values using robust multi-array average procedure RMA (48) of Bioconductor affy package.

Average signature expression and signature scores. Average signature expression was calculated as the standardized average expression

of all signature genes in sample subgroups (e.g. p53 signatures; p53 IHC status, ICMT 201609_x_at probe set). Signature scores were obtained summarizing the standardized expression levels of signature genes into a combined score with zero mean (32). The values shown in graphs are thus dimensionless.

Kaplan–Meier survival analysis. To identify two groups of tumors with either high or low ICMT signature, we used the classifier described in (32), that is a classification rule based on the ICMT signature score (201609_x_at probe set). Tumors were classified as ICMT signature ‘Low’ if the

combined score was negative and as ICMT signature ‘High’ if the combined score was positive. This classification was applied to expression values of the metadataset. To evaluate the prognostic value of the ICMT signature, we estimated, using the Kaplan–Meier method, the probabilities that patients would remain free of metastasis. To confirm these findings, the Kaplan–Meier curves were compared using the log-rank (Mantel–Cox) test. P-values were calculated according to the standard normal asymptotic distribution. Survival analysis was performed in GraphPad Prism.

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Conflict of Interest

The authors declare that they have no conflicts of interest with the contents of this article.

References

1. Liang, P. H., Ko, T. P., and Wang, A. H. J. (2002) Structure, mechanism and function of prenyltransferases. *Eur. J. Biochem.* 269, 3339–3354
2. Smeland, T. E., Seabra, M. C., Goldstein, J. L., and Brown, M. S. (1994) Geranylgeranylated Rab proteins terminating in Cys-Ala-Cys, but not Cys-Cys, are carboxyl-methylated by bovine brain membranes in vitro. *Proc Natl Acad Sci U S A.* 1994. 91: 10712–10716
3. Manolaridis, I., Kulkarni, K., Dodd, R. B., Ogasawara, S., Zhang, Z., Bineva, G., O’Reilly, N., Hanrahan, S. J., Thompson, A. J., Cronin, N., Iwata, S., and Barford, D. (2013) Mechanism of farnesylated CAAX protein processing by the intramembrane protease Rce1. *Nature.* 2013. 504:301–305
4. Winter-Vann, A. M., and Casey, P. J. (2005) Post-prenylation-processing enzymes as new targets in oncogenesis. *Nat. Rev. Cancer.* 5, 405–412
5. Maurer-Stroh, S., Koranda, M., Benetka, W., Schneider, G., Sirota, F. L., and Eisenhaber, F. (2007) Towards complete sets of farnesylated and geranylgeranylated proteins. *PLoS Comput. Biol.* 3, 634–648
6. Nguyen, U. T. T., Guo, Z., Delon, C., Wu, Y., Deraeve, C., Fränzel, B., Bon, R. S., Blankenfeldt, W., Goody, R. S., Waldmann, H., Wolters, D., and Alexandrov, K. (2009) Analysis of the eukaryotic prenylome by isoprenoid affinity tagging. *Nat Chem Biol.* 2009. 5, 227–35
7. Wang, M., and Casey, P. J. (2016) Protein prenylation: unique fats make their mark on biology. *Nat. Rev. Mol. Cell Biol.* 17, 110–122
8. Hancock, J. F., Magee, A. I., Childs, J. E., and Marshall, C. J. (1989) All ras proteins are polyisoprenylated but only some are palmitoylated. *Cell.* 57, 1167–1177
9. Casey, P. J., Solski, P. A., Der, C. J., and Buss, J. E. (1989) p21ras is modified by a farnesyl

- isoprenoid. *Proc. Natl. Acad. Sci.* 86, 8323–8327
10. Brown, M. S., and Goldstein, J. L. (1980) Multivalent feedback regulation of HMG CoA reductase, a control mechanism coordinating isoprenoid synthesis and cell growth. *J. Lipid Res.* 21, 505–17
11. Quesney-Huneus, V., Wiley, M. H., and Siperstein, M. D. (1979) Essential role for mevalonate synthesis in DNA replication. *Proc. Natl. Acad. Sci. U. S. A.* 76, 5056–60
12. Habenicht, A. J. R., Glomset, J. A., and Ross, R. (1980) Relation of cholesterol and mevalonic acid to the cell cycle in smooth muscle and Swiss 3T3 cells stimulated to divide by platelet-derived growth factor. *J. Biol. Chem.* 255, 5134–5140
13. Bergo, M. O., Gavino, B. J., Hong, C., Beigneux, A. P., McMahon, M., Casey, P. J., and Young, S. G. (2004) Inactivation of Icmt inhibits transformation by oncogenic K-Ras and B-Raf. *J. Clin. Invest.* 113, 539–550
14. Wahlstrom, A. M., Cutts, B. A., Liu, M., Lindskog, A., Karlsson, C., Sjogren, A. K., Andersson, K. M., Young, S. G., and Bergo, M. O. (2008) Inactivating Icmt ameliorates K-RAS-induced myeloproliferative disease. *Blood.* 112, 1357–1365
15. Lau, H., Tang, J., Casey, P. J., and Wang, M. (2017) Isoprenylcysteine carboxylmethyltransferase is critical for malignant transformation and tumor maintenance by all RAS isoforms. *Oncogene.* 36, 3934–3942
16. Court, H., Amoyel, M., Hackman, M., Lee, K. E., Xu, R., Miller, G., Bar-Sagi, D., Bach, E. A., Bergo, M. O., and Philips, M. R. (2013) Isoprenylcysteine carboxylmethyltransferase deficiency exacerbates KRAS-driven pancreatic neoplasia via Notch suppression. *J. Clin. Invest.* 123, 4681–4694
17. Cushman, I., and Casey, P. J. (2011) RHO methylation matters: A role for isoprenylcysteine carboxylmethyltransferase in cell migration and adhesion. *Cell Adhes. Migr.* 5, 11–15
18. Jansen, S., Gosens, R., Wieland, T., and Schmidt, M. (2018) Paving the Rho in cancer metastasis: Rho GTPases and beyond. *Pharmacology and Therapeutics.* 2018, 183:1-21
19. Cushman, I., and Casey, P. J. (2009) Role of isoprenylcysteine carboxylmethyltransferase-catalyzed methylation in Rho function and migration. *J. Biol. Chem.* 284, 27964–27973
20. Do, M. T., Chai, T. F., Casey, P. J., and Wang, M. (2017) Isoprenylcysteine carboxylmethyltransferase function is essential for RAB4A-mediated integrin $\beta 3$ recycling, cell migration and cancer metastasis. *Oncogene.* 36, 5757–5767
21. Zandvakili, I., Lin, Y., Morris, J. C., and Zheng, Y. (2017) Rho GTPases: Anti-or pro-neoplastic targets? *Oncogene.* 36, 3213–3222
22. Backlund, P. S. (1997) Post-translational processing of RhoA. Carboxyl methylation of the carboxyl-terminal prenylcysteine increases the half-life of RhoA. *J. Biol. Chem.* 272, 33175–33180
23. Roberts, P. J., Mitin, N., Keller, P. J., Chenette, E. J., Madigan, J. P., Currin, R. O., Cox, A. D., Wilson, O., Kirschmeier, P., and Der, C. J. (2008) Rho family GTPase modification and dependence on CAAX motif-signaled posttranslational modification. *J. Biol. Chem.* 283, 25150–25163
24. Gentry, L. R., Nishimura, A., Cox, A. D., Martin, T. D., Tsygankov, D., Nishida, M., Elston, T. C., and Der, C. J. (2015) Divergent roles of CAAX motif-signaled posttranslational modifications in the regulation and subcellular localization of Ral GTPases. *J. Biol. Chem.* 290, 22851–22861
25. Girardini, J. E., Napoli, M., Piazza, S., Rustighi, A., Marotta, C., Radaelli, E., Capaci, V., Jordan, L., Quinlan, P., Thompson, A., Mano, M., Rosato, A., Crook, T., Scanziani, E., Means, A. R., Lozano, G., Schneider, C., and Del Sal, G. (2011) A Pin1/Mutant p53 Axis Promotes Aggressiveness in Breast Cancer. *Cancer Cell.* 20, 79–91
26. Kasthuber, E. R., and Lowe, S. W. (2017) Putting p53 in Context. *Cell.* 170, 1062–1078
27. Kandoth, C., McLellan, M. D., Vandin, F., Ye, K., Niu, B., Lu, C., Xie, M., Zhang, Q., McMichael, J. F., Wyczalkowski, M. A., Leiserson, M. D., Miller, C. A., Welch, J. S., Walter, M. J., Wendl, M. C., Ley, T. J., Wilson, R. K., Raphael, B. J., and Ding, L. (2013) Mutational landscape and significance across 12 major cancer types. *Nature.* 502, 333–339
28. Soussi, T., and Wiman, K. G. (2007) Shaping Genetic Alterations in Human Cancer: The p53 Mutation Paradigm. *Cancer Cell.* 12, 303–312
29. Muller, P. A. J., and Vousden, K. H. (2014) Mutant p53 in cancer: New functions and therapeutic opportunities. *Cancer Cell.* 25, 304–317
30. Freed-Pastor, W. A., and Prives, C. (2012) Mutant p53: one name, many proteins. *Genes Dev.* 26,

- 1268–1286
31. Girardini, J. E., Walerych, D., and Del Sal, G. (2014) Cooperation of p53 mutations with other oncogenic alterations in cancer. *Subcell.Biochem.* 85, 41–70
32. Adorno, M., Cordenonsi, M., Montagner, M., Dupont, S., Wong, C., Hann, B., Solari, A., Bobisse, S., Rondina, M. B., Guzzardo, V., Parenti, A. R., Rosato, A., Biciato, S., Balmain, A., and Piccolo, S. (2009) A Mutant-p53/Smad Complex Opposes p63 to Empower TGFb-Induced Metastasis. *Cell.* 137, 87–98
33. Bouaoun, L., Sonkin, D., Ardin, M., Hollstein, M., Byrnes, G., Zavadil, J., and Olivier, M. (2016) TP53 Variations in Human Cancers: New Lessons from the IARC TP53 Database and Genomics Data. *Hum. Mutat.* 37, 865–876
34. Muller, P. A., and Vousden, K. H. (2013) p53 mutations in cancer. *Nat.Cell Biol.* 15, 2–8
35. Vassilev, L. T., Vu, B. T., Graves, B., Carvajal, D., Podlaski, F., Filipovic, Z., Kong, N., Kammlott, U., Lukacs, C., Klein, C., Fotouhi, N., and Liu, E. A. (2004) In vivo activation of the p53 pathway by small-molecule antagonists of MDM2. *Science.* 303, 844–848
36. Dai, Q., Choy, E., Chiu, V., Romano, J., Slivka, S. R., Steitz, S. A., Michaelis, S., and Philips, M. R. (1998) Mammalian prenylcysteine carboxyl methyltransferase is in the endoplasmic reticulum. *J.Biol.Chem.* 273, 15030–15034
37. Miller, L. D., Smeds, J., George, J., Vega, V. B., Vergara, L., Ploner, A., Pawitan, Y., Hall, P., Klaar, S., Liu, E. T., and Bergh, J. (2005) An expression signature for p53 status in human breast cancer predicts mutation status, transcriptional effects, and patient survival. *Proc.Natl.Acad.Sci.USA.* 102, 13550–13555
38. Soussi, T., and Beroud, C. (2001) Assessing TP53 status in human tumours to evaluate clinical outcome. *Nat. Rev. Cancer.* 1, 233–240
39. Bergo, M. O., Leung, G. K., Ambroziak, P., Otto, J. C., Casey, P. J., Gomes, A. Q., Seabra, M. C., and Young, S. G. (2001) Isoprenylcysteine Carboxyl Methyltransferase Deficiency in Mice. *J. Biol. Chem.* 276, 5841–5845
40. Zhou, H. C., Fang, J. H., Luo, X., Zhang, L., Yang, J., Zhang, C., and Zhuang, S. M. (2014) Downregulation of microRNA-100 enhances the ICMT-Rac1 signaling and promotes metastasis of hepatocellular carcinoma cells. *Oncotarget.* 5, 12177–12188
41. Sullivan, K. D., Galbraith, M. D., Andrysk, Z., and Espinosa, J. M. (2017) Mechanisms of transcriptional regulation by p53. *Cell Death Diff.* 25, 133–143
42. Wang, B.; Xiao, Z.; Ko, H.L. and Ren, E. (2010) The p53 response element and transcriptional repression. *Cell Cycle.* 9, 870–879
43. Freed-Pastor, W. A., Mizuno, H., Zhao, X., Langerod, A., Moon, S. H., Rodriguez-Barrueco, R., Barsotti, A., Chicas, A., Li, W., Polotskaia, A., Bissell, M. J., Osborne, T. F., Tian, B., Lowe, S. W., Silva, J. M., Borresen-Dale, A. L., Levine, A. J., Bargonetti, J., and Prives, C. (2012) Mutant p53 disrupts mammary tissue architecture via the mevalonate pathway. *Cell.* 148, 244–258
44. Sorrentino, G., Ruggeri, N., Specchia, V., Cordenonsi, M., Mano, M., Dupont, S., Manfrin, A., Ingallina, E., Sommaggio, R., Piazza, S., Rosato, A., Piccolo, S., and Del Sal, G. (2014) Metabolic control of YAP and TAZ by the mevalonate pathway. *Nat. Cell Biol.* 16, 357–366
45. Mantovani, F., Tocco, F., Girardini, J., Smith, P., Gasco, M., Lu, X., Crook, T., and Del Sal, G. (2007) The prolyl isomerase Pin1 orchestrates p53 acetylation and dissociation from the apoptosis inhibitor iASPP. *Nat. Struct. Mol. Biol.* 14, 912–920
46. Guida, E., Bisso, A., Fenollar-Ferrer, C., Napoli, M., Anselmi, C., Girardini, J. E., Carloni, P., and Del Sal, G. (2008) Peptide aptamers targeting mutant p53 induce apoptosis in tumor cells. *Cancer Res.* 68, 6550–6558
47. Enzo, E., Santinon, G., Pocaterra, A., Aragona, M., Bresolin, S., Forcato, M., Grifoni, D., Pession, A., Zanconato, F., Guzzo, G., Biciato, S., and Dupont, S. (2015) Aerobic glycolysis tunes YAP/TAZ transcriptional activity. *EMBO J.* 34, 1349–1370
48. Irizarry, R. A., Bolstad, B. M., Collin, F., Cope, L. M., Hobbs, B., and Speed, T. P. (2003) Summaries of Affymetrix GeneChip probe level data. *Nucleic Acids Res.* 31, e15

Figure 1. Mutant and wt p53 differentially regulate ICMT expression. **a)** MDA-MB-231 cells were transfected with p53 or control siRNA (sip53 or siControl) and mRNA levels were determined by qRT-PCR. ICMT mRNA levels were normalized to GAPDH mRNA and expressed as fold change comparing with control condition (Upper panel, n=3, One-tailed T-test, p = 0.0062). ICMT and p53R280K levels were determined by western blot (Lower panel). The effect of endogenous p53R273H knock down on ICMT expression was analyzed similarly in **b)** MDA-MB-468 cells (n=3, One-tailed T-test, p = 0.048) or **c)** HT29 cells (n=3, One-tailed T-test, p = 0.0151). **d)** H1299 cells were transfected with plasmids expressing wt p53, p53R280K or empty vector (ctrl) as indicated. ICMT mRNA levels were determined by qRT-PCR, normalized relative to GAPDH mRNA and expressed as fold change comparing with control cells (n=4, One tailed T-test, p = 0.0147 and p = 0.0123 respectively). Western blot analysis of ICMT and p53 protein levels (Lower panel). **e)** MCF-7 (Upper panel) or HCT116 p53^{+/+} cells (Lower panel) were treated with nutlin-3 and protein levels were analyzed by western blot. **f)** The effect of wt p53 on ICMT mRNA levels was determined by qRT-PCR upon transfection of HCT116 p53^{-/-} cells with a plasmid expressing wt p53 or empty vector as a control, (Upper panel; n=4, One-tailed T-test, p = 0.0218). ICMT and wt p53 expression was analyzed by western blot (Lower panel).

Figure 2. Mutant and wt p53 differentially regulate the ICMT promoter. **a)** Luciferase assays in H1299 cells co-transfected with pICMTluc, plasmids expressing the indicated proteins or empty vector (control), and pCMV-β-gal. Luciferase values were normalized to β-galactosidase activity and expressed as fold change relative to cells transfected with empty vector (One tailed T-test, * : p< 0.05 and *** : p< 0.0001). **b)** Western blot analysis confirming p53R280K, p53R273H, p53R248W, p53R249S, p53R175H and wt p53 expression upon transfection in H1299 cells in luciferase assays from figure 2a. **c)** Luciferase assays in HCT116 p53^{-/-} or HCT116 p53^{+/+} cells co-transfected with pICMTluc, pCMV-β-gal and treated with doxorubicin (Upper panel; One tailed T-test, p = 0.0062). Western blot analysis confirming wt p53 induction in HCT116 p53^{+/+} cells upon doxorubicin treatment (Lower panel). **d)** Mutant p53R280K counteracts the repressive effect of wt p53 on the ICMT reporter. Luciferase assays were performed on H1299 cells co-transfected with pICMTluc and plasmids expressing wt p53 and p53R280K as indicated (One way ANOVA, p< 0.0001).

Figure 3. Effect of wt p53 on the ICMT promoter. **a)** Schematic representation of ICMT promoter deletions used to generate reporter plasmids. **b)** Luciferase assays on promoter deletions. H1299 cells were co-transfected with the indicated reporters and a plasmid expressing wt p53 or empty vector (control). Luciferase activity was normalized to β-galactosidase and expressed as arbitrary units (Two way ANOVA, ** : p< 0.01 and *** : p< 0.001). **c)** Luciferase assays on H1299 cells co-transfected with pCDNA3-wtp53 and pGL3 promoter vector (pGL3P) or pGL3 promoter containing the 195 bp (-209 -14) fragment (pGL3P-ICMTluc200-50) as indicated. Luciferase activity was normalized and expressed as fold change comparing with control cells (transfected with pCDNA3), (One-tailed T-test, p = 0.01). Lower panel: confirmation of wt p53 expression by western blot. **d)** Luciferase assays on H1299 cells co-transfected with pICMTlucΔ(-209-14) and a plasmid expressing wt p53 or empty vector (control). Luciferase activity was normalized and expressed as fold change comparing with control cells. Lower panel: confirmation of wt p53 expression by western blot. **e)** ChIP assay on H1299 cells co-transfected with pICMTluc and pCDNA3-wtp53 or pCDNA3 as a control. IP was performed using anti-p53 antibody (DO1). The presence of ICMT promoter DNA in immunoprecipitates was determined by q-PCR (Upper panel, n=3, One-tailed T-test, p = 0.026) and semiquantitative PCR (Lower panel).

Figure 4. Effect of mutant p53 on the ICMT promoter. **a)** Luciferase assays on promoter deletions. H1299 cells were co-transfected with the indicated reporters and a plasmid expressing p53R280K or empty vector (control). Luciferase activity was normalized to β-galactosidase activity and expressed as arbitrary units (Two way ANOVA, *** : p< 0.001). **b)** Luciferase assays on H1299 cells co-transfected with pICMTlucΔ(-209-14) and a plasmid expressing p53R280K or empty vector (control). Luciferase activity was

normalized and expressed as fold change comparing with control cells (One-tailed T-test, $p = 0.0256$). Lower panel: confirmation of p53R280K expression by western blot. **c)** ChIP assay on H1299 cells co-transfected with pICMTluc and pCDNA3-p53R280K or pCDNA3 as a control. IP was performed using anti-p53 antibody (DO1). The presence of the -2178 -2071 (ICMTup) or the -66 +36 (ICMTdown) promoter fragments in immunoprecipitates was determined by qPCR (Upper panel, $n=3$, One-tailed T-test, $p = 0.0476$) and semiquantitative PCR (Lower panel).

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Figure 6. Expression levels of ICMT in breast and lung cancer. Standardized expression levels of ICMT in samples from the breast cancer compendium ($n=3661$) stratified according to **a)** high and low mutant p53 and high and low wt p53 expression signature score (see text) and **b)** p53 IHC status. Standardized expression levels of ICMT in lung adenocarcinoma samples from the TCGA-LUAD dataset ($n=516$) stratified according to **c)** high and low mutp53 and high and low wt p53 expression signature score and **d)** p53 status as determined from whole exome sequencing (**** : $p\text{-value} < 0.0001$ and * : $p\text{-value} < 0.05$ in a two-tailed unpaired t-test).

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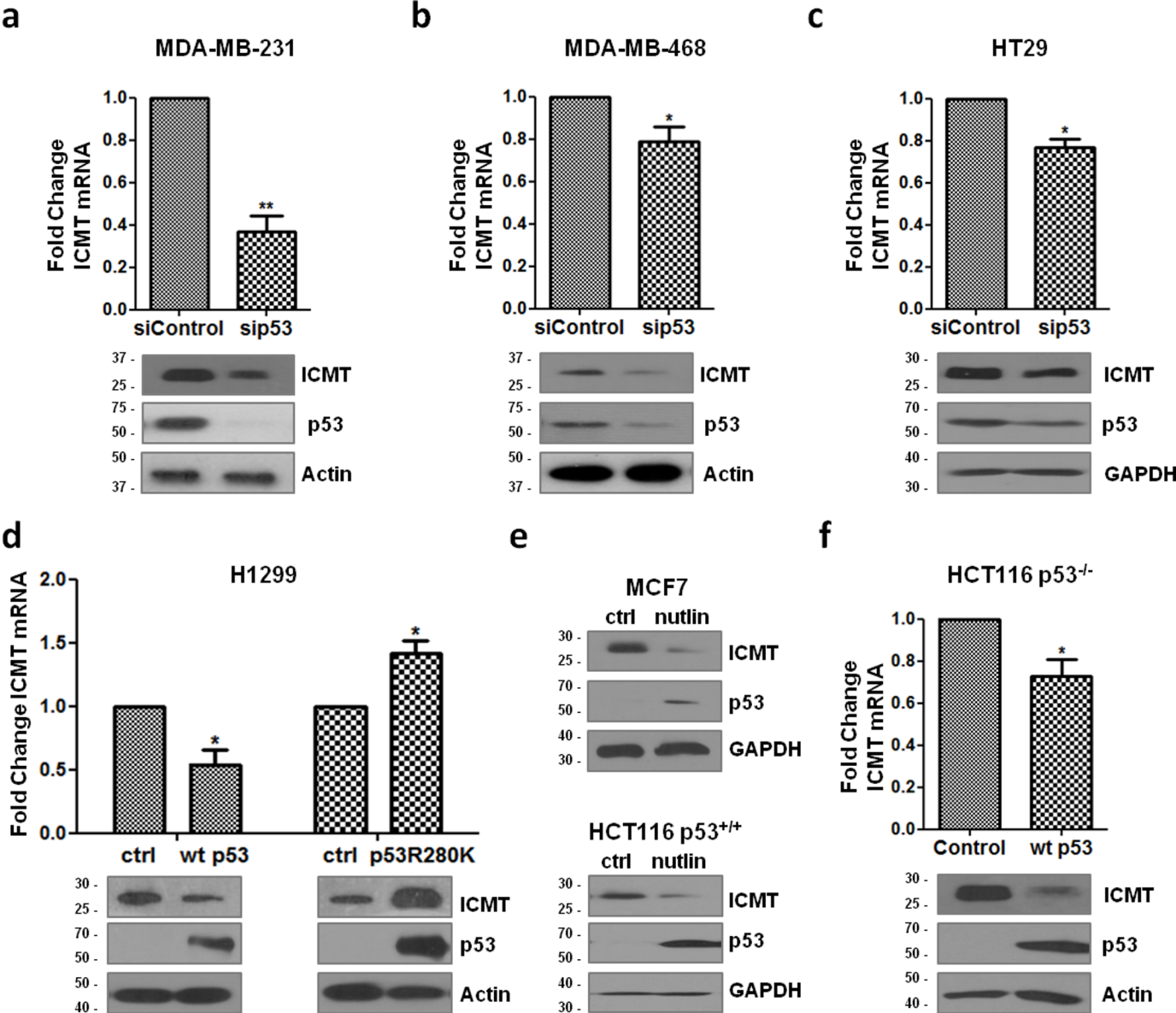


Figure 1. Mutant and wt p53 differentially regulate *ICMT* expression. a) MDA-MB-231 cells were transfected with p53 or control siRNA (sip53 or siControl) and mRNA levels were determined by qRT-PCR. ICMT mRNA levels were normalized to GAPDH mRNA and expressed as fold change comparing with control condition (Upper panel, n=3, One-tailed T-test, p = 0.0062). ICMT and p53R280K levels were determined by western blot (Lower panel). The effect of endogenous p53R273H knock down on *ICMT* expression was analyzed similarly in **b)** MDA-MB-468 cells (n=3, One-tailed T-test, p = 0.048) or **c)** HT29 cells (n=3, One-tailed T-test, p = 0.0151). **d)** H1299 cells were transfected with plasmids expressing wt p53, p53R280K or empty vector (ctrl) as indicated. ICMT mRNA levels were determined by qRT-PCR, normalized relative to GAPDH mRNA and expressed as fold change comparing with control cells (n=4, One-tailed T-test, p = 0.0147 and p = 0.0123 respectively). Western blot analysis of ICMT and p53 protein levels (Lower panel). **e)** MCF-7 (Upper panel) or HCT116 p53^{+/+} cells (Lower panel) were treated with nutlin-3 and protein levels were analyzed by western blot. **f)** The effect of wt p53 on ICMT mRNA levels was determined by qRT-PCR upon transfection of HCT116 p53^{-/-} cells with a plasmid expressing wt p53 or empty vector as a control, (Upper panel; n=4, One-tailed T-test, p = 0.0218). ICMT and wt p53 expression was analyzed by western blot (Lower panel).

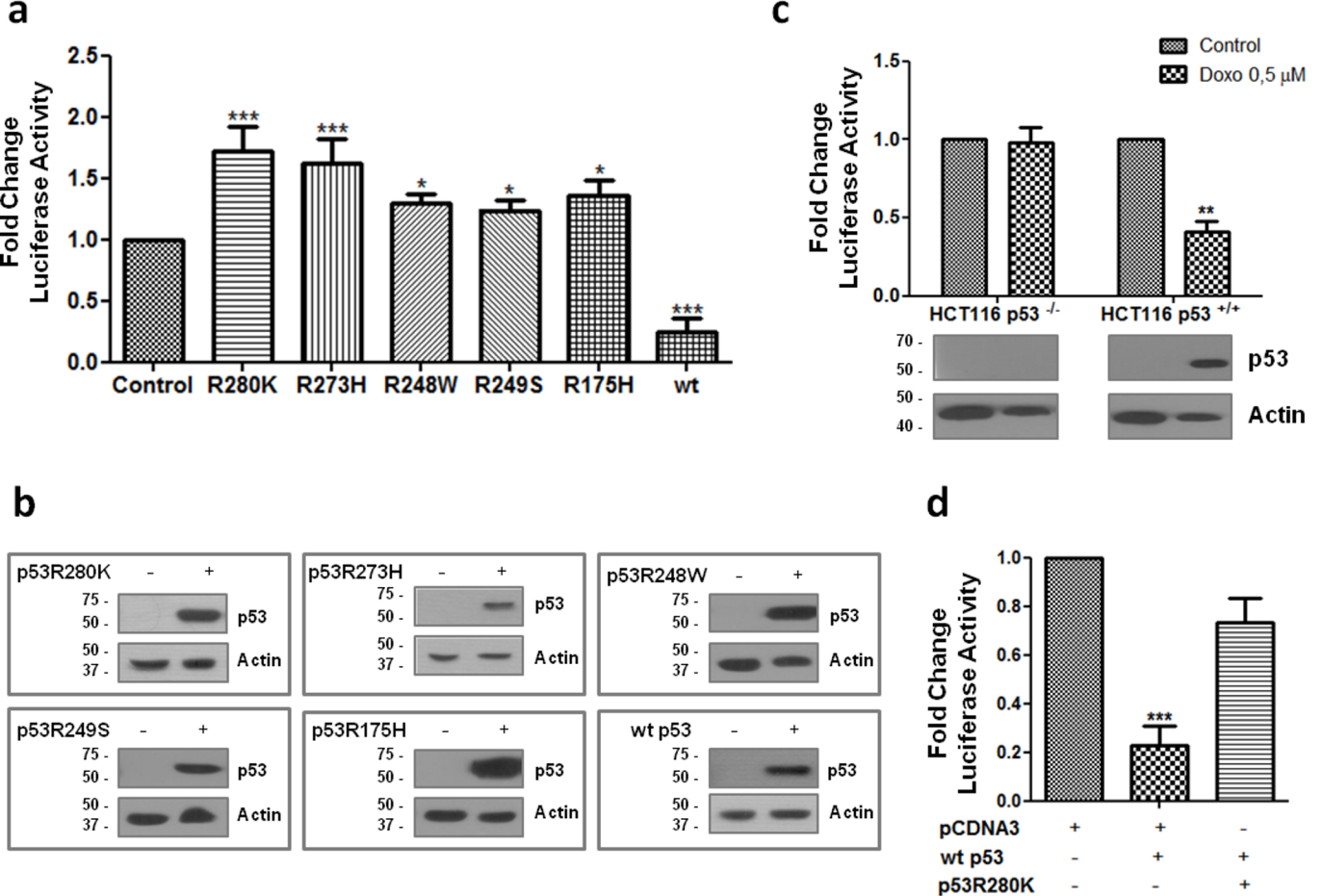


Figure 2. Mutant and wt p53 differentially regulate the *ICMT* promoter. **a)** Luciferase assays in H1299 cells co-transfected with pICMTluc, plasmids expressing the indicated proteins or empty vector (control), and pCMV- β -gal. Luciferase values were normalized to β -galactosidase activity and expressed as fold change relative to cells transfected with empty vector (One tailed T-test, *: $p < 0.05$ and *** : $p < 0.0001$). **b)** Western blot analysis confirming p53R280K, p53R273H, p53R248W, p53R249S, p53R175H and wt p53 expression upon transfection in H1299 cells in luciferase assays from figure 2a. **c)** Luciferase assays in HCT116 p53^{-/-} or HCT116 p53^{+/+} cells co-transfected with pICMTluc, pCMV- β -gal and treated with doxorubicin (Upper panel; One tailed T-test, $p = 0.0062$). Western blot analysis confirming wt p53 induction in HCT116 p53^{+/+} cells upon doxorubicin treatment (Lower panel). **d)** Mutant p53R280K counteracts the repressive effect of wt p53 on the *ICMT* reporter. Luciferase assays were performed on H1299 cells co-transfected with pICMTluc and plasmids expressing wt p53 and p53R280K as indicated (One way ANOVA, $p < 0.0001$).

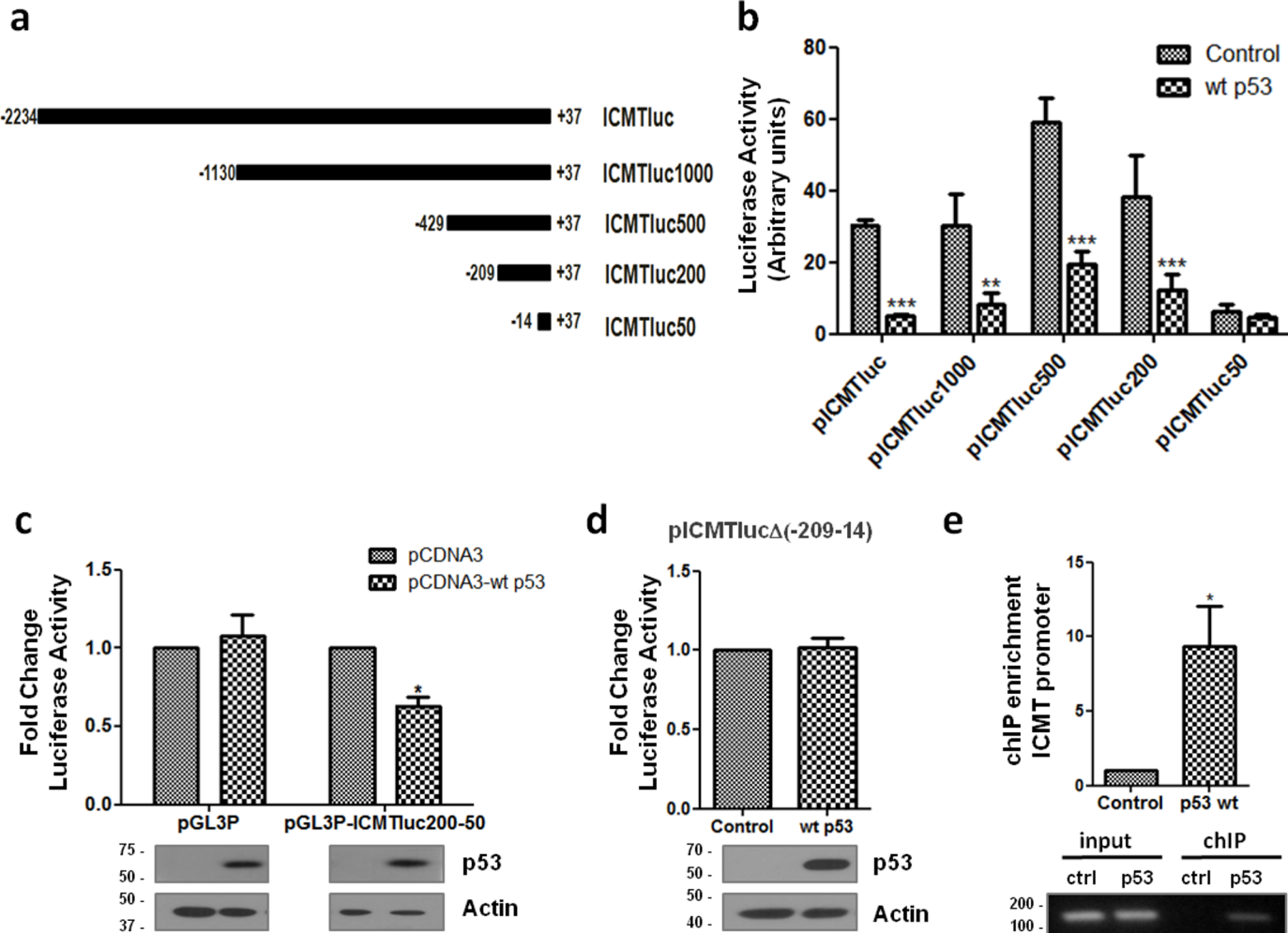


Figure 3. Effect of wt p53 on the ICMT promoter. **a)** Schematic representation of ICMT promoter deletions used to generate reporter plasmids. **b)** Luciferase assays on promoter deletions. H1299 cells were co-transfected with the indicated reporters and a plasmid expressing wt p53 or empty vector (control). Luciferase activity was normalized to β -galactosidase activity and expressed as arbitrary units (Two way ANOVA, ** : $p < 0.01$ and *** : $p < 0.001$). **c)** Luciferase assays on H1299 cells co-transfected with pCDNA3-wtp53 and pGL3 promoter vector (pGL3P) or pGL3 promoter containing the 195 bp (-209 -14) fragment (pGL3P-ICMTluc200-50) as indicated. Luciferase activity was normalized and expressed as fold change comparing with control cells (transfected with pCDNA3), (One-tailed T-test, $p = 0.01$). Lower panel: confirmation of wt p53 expression by western blot. **d)** Luciferase assays on H1299 cells co-transfected with pICMTluc Δ (-209-14) and a plasmid expressing wt p53 or empty vector (control). Luciferase activity was normalized and expressed as fold change comparing with control cells. Lower panel: confirmation of wt p53 expression by western blot. **e)** ChIP assay on H1299 cells co-transfected with pICMTluc and pCDNA3-wtp53 or pCDNA3 as a control. IP was performed using anti-p53 antibody (DO1). The presence of ICMT promoter DNA in immunoprecipitates was determined by q-PCR (Upper panel, $n=3$, One-tailed T-test, $p = 0.026$) and semiquantitative PCR (Lower panel).

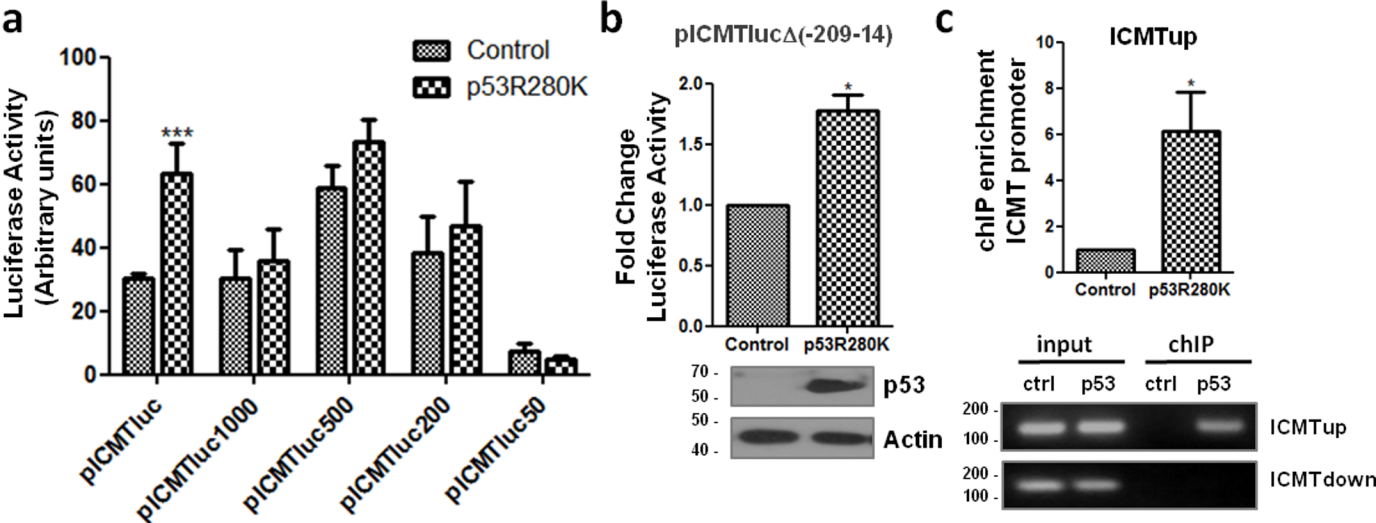


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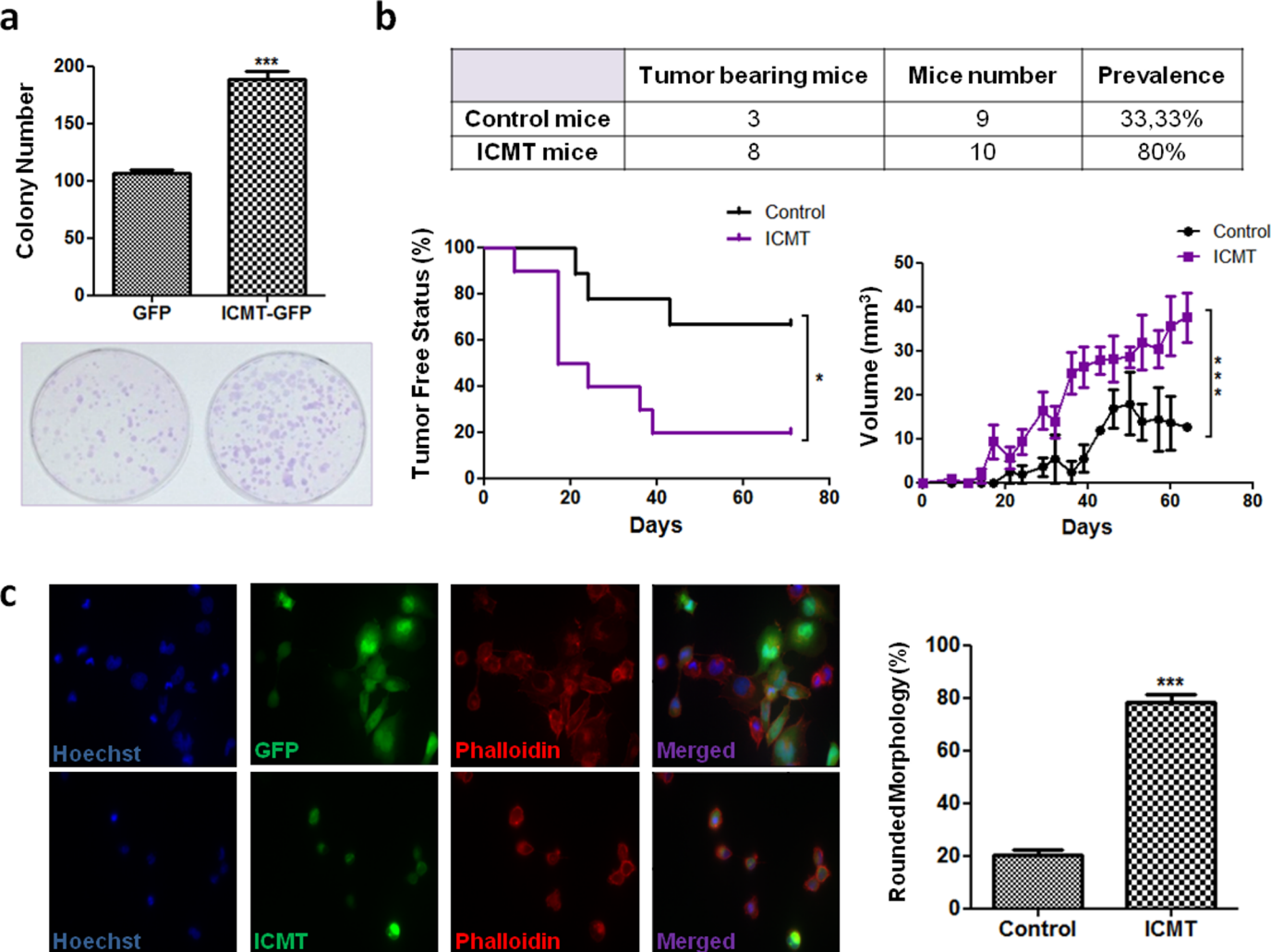


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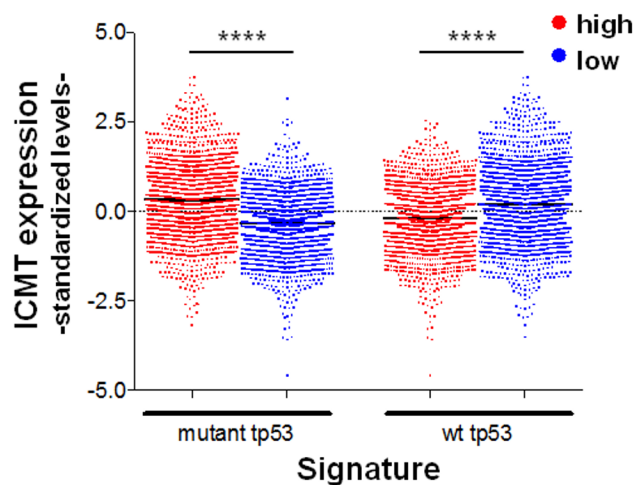
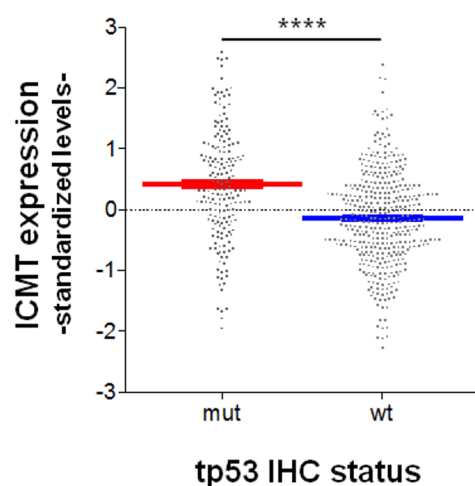
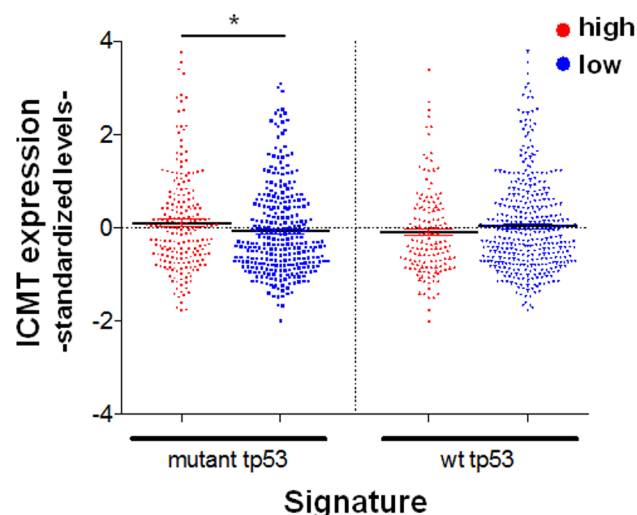
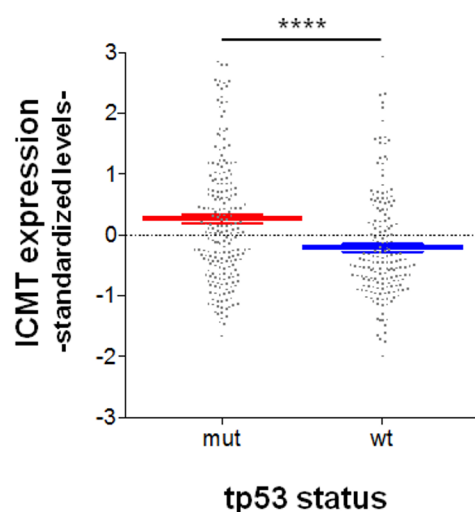
a**b****c****d**

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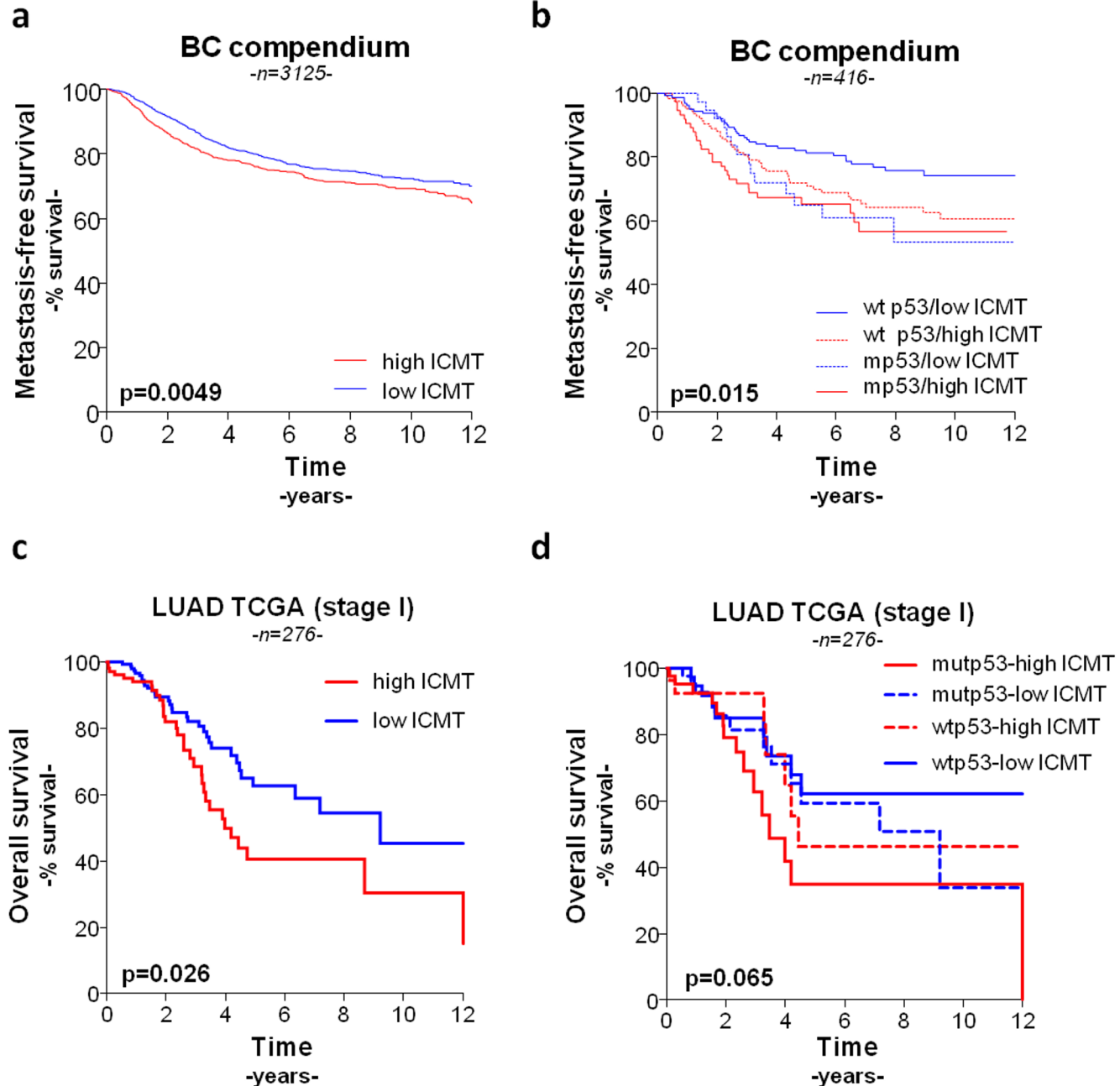


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Isoprenylcysteine carboxy methyltransferase (ICMT) is associated with tumor aggressiveness and its expression is controlled by the p53 tumor suppressor
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