Senescence Sensitivity of Breast Cancer Cells Is Defined by Positive Feedback Loop between CIP2A and E2F1

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ABSTRACT
Senescence induction contributes to cancer therapy responses and is crucial for p53-mediated tumor suppression. However, whether p53 inactivation actively suppresses senescence induction has been unclear. Here, we show that E2F1 overexpression, due to p53 or p21 inactivation, promotes expression of human oncoprotein CIP2A, which in turn, by inhibiting PP2A activity, increases stabilizing serine 364 phosphorylation of E2F1. Several lines of evidence show that increased activity of E2F1-CIP2A feedback renders breast cancer cells resistant to senescence induction. Importantly, mammary tumorigenesis is impaired in a CIP2A-deficient mouse model, and CIP2A-deficient tumors display markers of senescence induction. Moreover, high CIP2A expression predicts for poor prognosis in a subgroup of patients with breast cancer treated with senescence-inducing chemotherapy. Together, these results implicate the E2F1-CIP2A feedback loop as a key determinant of breast cancer cell sensitivity to senescence induction. This feedback loop also constitutes a promising prosenescence target for therapy of cancers with an inactivated p53–p21 pathway.

SIGNIFICANCE: It has been recently realized that most currently used chemotherapies exert their therapeutic effect at least partly by induction of terminal cell arrest, senescence. However, the mechanisms by which cell-intrinsic senescence sensitivity is determined are poorly understood. Results of this study identify the E2F1-CIP2A positive feedback loop as a key determinant of breast cancer cell sensitivity to senescence induction. Our data also indicate that this newly characterized interplay between 2 frequently overexpressed oncoproteins constitutes a promising prosenescence target for therapy of cancers with inactivated p53 and p21. Finally, these results may also facilitate novel stratification strategies for selection of patients to receive senescence-inducing cancer therapies.

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INTRODUCTION
Cellular senescence functions as a barrier that normal cells have to overcome to transform into cancer cells (1). Accordingly, analysis of several types of premalignant tumors, most notably benign skin nevi, has revealed the existence of senescent precancerous cells (1, 2). The functional relevance of spontaneous senescence induction in preventing tumor initiation and progression has been shown by several recent mouse studies (3–5).

Notably, although traditionally considered as apoptosis-inducing agents, most of the currently used chemotherapies exert their therapeutic effect at least partly by senescence induction (6, 7). Similarly, evidence is accumulating that despite the essential role of the tumor suppressor p53 in mediating apoptosis induction by genotoxic stimuli and chemotherapies, its in vivo tumor suppressor activity is not dependent on apoptosis, but rather on senescence induction (8–11). However, p53 function is inactivated in the majority of human cancers, and p53 inactivation correlates with poor patient survival in several cancer types including breast cancer (12). Traditionally, resistance of p53-mutant cells to chemotherapy has been linked to defective checkpoint function of p53 (13). However, we cannot exclude the possibility that, in addition to defective checkpoint activity, p53 inhibition actively promotes a mechanism or mechanisms that confer cancer cells’ general resistance to chemotherapy-induced senescence. In addition to mutations, p53 is known to be inactivated in cancer cells by enhanced proteolytic degradation driven by the ubiquitin ligases MDM2 and MDMX (14). Although therapeutic strategies to activate senescence via inhibition of MDM2/MDMX-p53 interactions have been under intense research lately (14), because of p53 mutations, they are unlikely to be efficient in a large fraction of human cancers.
tumors. Therefore, the need to identify novel mechanisms that promote senescence resistance and tumor progression downstream of inactivated p53 is urgent. Identification of such mechanisms would not only provide novel insights into senescence regulation but could also facilitate development of novel prosenescence therapeutic strategies for cancers harboring inactivated p53 (6, 7).

E2F1 is an oncogenic transcription factor that is overexpressed in various human cancer types (15). Recent studies have indicated that E2F1’s classic function in transcriptional activation of S-phase–associated genes only partially explains its oncogenic activity (15, 16). Its transcriptional activity is negatively regulated by p53 through p21-mediated regulation of retinoblastoma (Rb) protein phosphorylation (15, 16), but expression and activity of E2F1 are also regulated directly by phosphorylation, independently of Rb (16, 17). The p53 reactivation by small-molecule activator Nutlin-3 inhibits protein expression of E2F1 and induces senescence-like growth arrest (18). Accordingly, knockdown of E2F1 expression also induces cellular senescence in p53-deficient cancer cells and blocks tumor growth (19–21). However, the mechanisms by which E2F1 prevents senescence induction in p53-deficient cells are currently unclear.

The human oncoprotein cancerous inhibitor of PP2A (CIP2A) is overexpressed in 65% to 90% of tissues from patients in almost all human cancer types studied thus far, and its expression correlates with cancer progression in a large variety of human malignancies (Supplementary Table S1; refs. 22–25). Even though CIP2A protein expression correlates with proliferation in human cancers (22–25), expression of CIP2A is not regulated by cell-cycle activity (24). Overexpressed CIP2A transforms immortalized cells of either human or mouse origin (23, 26), whereas its depletion by RNA interference (RNAi) inhibits anchorage-independent growth of several types of tumor cells (22–26). CIP2A's tumor-promoting role has been shown by several xenograft studies (22, 23, 25, 26), whereas its depletion by RNA interference (RNAi) inhibits anchorage-independent growth of several types of tumor cells (22–26). CIP2A's tumor-promoting role in cultured mouse embryonic fibroblasts (MEF), and CIP2A expression is regulated by a p53-dependent mechanism, we treated isogenic WT and p53−/− cells, CIP2A protein expression was inhibited in a concentration-dependent manner (Fig. 1G and H). To study whether wild-type (WT) p53 negatively regulates CIP2A expression, p53 expression was inhibited by siRNA in cultured mouse embryonic fibroblasts (MEF), and CIP2A expression was subsequently studied by Western blotting. As shown in Fig. 1C, inhibition of p53 expression in MEFs by 2 different siRNA sequences resulted in robust induction of CIP2A protein expression. Moreover, reaction of WT p53 in MCF-7 human breast cancer cells with small-molecule inhibitors of the Mdm2-p53 interaction, Nutlin-3 (31) or RITA (32), inhibited CIP2A expression at both the mRNA and protein levels (Fig. 1D and E and Supplementary Fig. S2A and S2B). To confirm that CIP2A downregulation by Nutlin-3 is dependent on WT p53 function, we treated MDA-MB-231 human breast cancer cells, harboring inactive mutant p53, with Nutlin-3. Nutlin-3 treatment had no effect on either p21 or CIP2A protein expression in MDA-MB-231 cells (Fig. 1F). However, when WT p53 was introduced to these cells, CIP2A protein expression was inhibited in a concentration-dependent manner (Fig. 1G). To further confirm that CIP2A expression is regulated by a p53-dependent mechanism, we treated isogenic WT and p53−/− HCT116 human colorectal cancer cells with the p53-activating chemotherapy doxorubicin. In contrast to WT cells, p53−/− HCT116 cells were resistant to doxorubicin-induced inhibition of CIP2A mRNA expression (Fig. 1H). In addition to in vitro models, we analyzed CIP2A expression in lymphoma tissue derived from a transgenic Eμ-Myc mouse model carrying tamoxifen-inducible p53 (33). As shown in Fig. 1I and J, in vivo restoration of p53 function resulted in inhibition of CIP2A expression in lymphoma tissue, thus confirming that p53 also negatively regulates oncoprotein CIP2A expression in vivo. Interestingly,
**Figure 1.** WT p53 negatively regulates CIP2A expression. A, representative immunohistochemical stainings of CIP2A and p53 expression in human breast cancer tumors. B, CIP2A expression positively correlates with p53 expression and with proliferation marker Ki-67 in human breast tumors (n = 1228). P value calculated by χ2 test. C, Western blot analysis of CIP2A expression in MEFs 48 h after transfection with scrambled (SCR) or 2 different p53 siRNAs (p53.1 and p53.2). D, Western blot analysis of CIP2A, p53, and p21 expression in MCF-7 cells treated with 2, 5, or 10 μmol/L of Nutlin-3 for 24 h. Shown is mean ± SEM of 3 independent experiments. E, CIP2A protein expression in MDA-MB-231 human breast cancer cells harboring DNA binding–deficient p53 treated with 5 μmol/L of Nutlin-3 for 24 h. Shown is mean ± SEM of 2 independent experiments. F, CIP2A protein expression in MDA-MB-231 human breast cancer cells harboring DNA binding–deficient p53 treated with 5 μmol/L of Nutlin-3 for 24 h. Shown is mean ± SEM of 2 independent experiments. G, Western blot analysis of CIP2A expression in MDA-MB-231 cells 48 h after transfection either with control (CTL) or with WT p53-expressing (p53) adenovirus using different multiplicity of infections (MOI). H, p21 and CIP2A mRNA expression from WT and p53−/− HCT116 cells treated with 0.2 μg/μL of doxorubicin (Doxo) for 0 (Ctrl), 24, or 48 h. Shown is mean ± SD of 2 experiments analyzed by qBasePLUS 1.0 analysis software. I, Representative Western blot analysis of CIP2A expression from tamoxifen-inducible Eμ-Myc/p53ER lymphomas treated systemically either with vehicle (−) or with tamoxifen (+). J, Quantitation of CIP2A protein levels from I. CIP2A protein expression normalized to β-actin. Shown is mean ± SD of 3 vehicle- and 4 tamoxifen-treated lymphoma lysates. K, Ingenuity Transcription Factor analysis of CIP2A-regulated gene expression changes in HeLa cells. D, and G, representative result of 2 independent experiments with similar results.

**E2F1 Upregulates CIP2A Expression Downstream of Inactivated p53**

To study whether p53 regulates CIP2A expression at the transcriptional level, MCF-7 cells transfected with a CIP2A promoter luciferase construct containing the 1802 bp upstream promoter fragment (30) were treated with Nutlin-3 or RITA. The p53 reactivation either of these compounds inhibited the activity of the CIP2A promoter but not the activity of the EGFR receptor (EGFR) promoter (35) that was used as a control (Fig. 2A and...
Supplementary Fig. S2C). Bioinformatic analysis of the −1802 fragment of the CIP2A promoter revealed 2 putative p53 binding sites (Fig. 2B and Supplementary Fig. S2D). However, when a chromatin immunoprecipitation assay for p53 was conducted in doxorubicin-treated HCT-116 cells, we could not detect any enrichment for these 2 putative binding sites, although p53 clearly accumulated on Mdm2 or p21 promoters (Fig. 2C). In support of these results, p53 was found not to bind to the CIP2A promoter in chromatin immunoprecipitation sequencing (ChIP-Seq) analysis conducted with control or Nutlin-3–treated MCF-7 cells (data not shown; S. Aerts; personal communication). These results indicate that although p53 activity inhibits CIP2A gene transcription, CIP2A is not a direct target gene of p53.

The p53 downstream target, p21, regulates gene expression by inhibiting cyclin-dependent kinases (CDK), which in turn leads to dephosphorylation of Rb protein and consequent inhibition of an oncogenic transcription factor E2F1 (15, 16). We confirmed that Nutlin-3–induced CIP2A downregulation is associated with the activation of the above-described p21 cascade, leading also to the previously observed inhibition of
E2F1 protein expression (ref. 18; Fig. 2D). To study whether p21 induction is required for p53-mediated CIP2A downregulation, we used isogenic HCT-116 WT and p21\textsuperscript{−/−} cells. In the unperturbed p21\textsuperscript{−/−} cells, CIP2A expression was increased, as compared with that in WT cells (Fig. 2E). Interestingly, similar to p53\textsuperscript{−/−} HCT-116 cells, p21\textsuperscript{−/−} HCT-116 cells also were resistant to doxorubicin-induced CIP2A inhibition (Fig. 2F). Moreover, p21 expression by adenoviral transduction inhibited E2F1 and CIP2A expression in MDA-MB-231 cells harboring mutated p53 (Fig. 2F). Importantly, p21-elicted E2F1 inhibition was detected already at a 24-hour time point (1 day) and preceded downregulation of CIP2A protein expression (Fig. 2F). These results suggest that increased E2F1 expression may stimulate CIP2A expression in cells with inactive p53 and p21. In support of this hypothesis, CIP2A expression was inhibited in cells transfected with E2F1-targeting siRNA (Fig. 2G). Of note, CIP2A downregulation by E2F1 RNA interference (RNAi) is unlikely to be caused by general inhibition of cell-cycle activity, as CIP2A expression neither is sensitive to aphidicolin-elicted cell-cycle arrest nor is associated with serum-induced cell-cycle progression (24). Furthermore, conditional tetracycline-induced overexpression of E2F1 resulted in CIP2A upregulation at the mRNA level (Fig. 2H). To verify that CIP2A is a direct E2F1 target, we conducted E2F1 ChIP in cells transfected with an E2F1 expression construct. The E2F1 binding site at −378 to −361 in the −1802 fragment of CIP2A promoter was predicted by using Genomatix software. As shown in Fig. 2I, E2F1 antibody immunoprecipitation clearly enriched this putative CIP2A promoter E2F1 binding site from E2F1-overexpressing cells as compared with cells transfected with control vector or nonantibody controls. E2F1 binding to CIP2A promoter was further verified by ChIP-Seq analysis from MCF-7 cells by using the ENCODE database (Supplementary Fig. S2E).

Taken together, these results strongly imply downregulation of CIP2A oncoprotein expression as a novel target mechanism for p53 tumor suppressor activity (Fig. 2J). Moreover, these results show that E2F1 stimulates CIP2A expression in cells with inactive p53 and p21 (Fig. 2J).

**Inhibition of CIP2A Expression Is a Prerequisite for p53-Mediated Senescence Induction**

In line with the indicated role for CIP2A as a p53 effector protein (Fig. 1K), CIP2A depletion by RNAi in MCF-7 cells mimicked p53-activated senescence, as characterized by increased senescence-associated β-galactosidase (SA-β-gal) activity and flattened cell morphology in most of the cells (Fig. 3A). Induction of senescence was verified in CIP2A siRNA-transfected MCF-7 cells by increased expression of the p53-induced senescence marker decoy receptor 2 (Dcr2; ref. 11; Fig. 3B). Importantly, CIP2A depletion also induced the appearance of the senescence phenotype in p53-mutant MDA-MB-231 cells (Fig. 3C), in which depletion of CIP2A causes long-term inhibition of xenograft tumor growth (22). Previously, we have shown that inhibition of CIP2A does not induce programmed cell death in HeLa cells (23). As hypothesized, stable expression of CIP2A did not reverse the obvious cell death phenotype in MCF-7 cells treated with RITA, a known inducer of p53-dependent cell death (Supplementary Fig. S2F and S2G; ref. 32). These results indicate that CIP2A downregulation is linked to p53-induced senescence.

To study whether CIP2A inhibition is truly required for p53-mediated senescence induction, Nutlin-3–induced CIP2A inhibition was prevented by infection of MCF-7 cells with CIP2A-expressing adenovirus. Of note, even though CIP2A overexpression did not prevent Nutlin-3–induced p21 induction (Fig. 3D), it prevented senescence induction in MCF-7 cells. This finding was indicated by a significant decrease in the number of cells displaying SA-β-gal activity and flattened cell morphology (Fig. 3E and F), as well as inhibition of induction of several Nutlin-3–regulated genes that previously have been shown to be functionally involved in p53-induced senescence (refs. 36–38; Fig. 3G).

Overexpression of CIP2A was recently shown to induce resistance to cell proliferation inhibition in doxorubicin-treated MCF-7 cells (39). In line with doxorubicin-elicted inhibition of CIP2A mRNA expression in a p53- and p21-dependent manner (Figs. 1I and 2E), protein expression of both E2F1 and CIP2A was also inhibited by doxorubicin treatment (Fig. 3H). Importantly, as for Nutlin-3, stable expression of CIP2A rescued MCF-7 cells from doxorubicin-induced senescence (Fig. 3I and J).
Figure 3. Inhibition of CIP2A expression is a prerequisite for p53-mediated senescence induction. A, SA-β-gal staining of MCF-7 cells 5 days after transfection either with scrambled (siSCR) or with CIP2A siRNA (siCIP2A). B, Western blot analysis of senescence marker DcR2 expression in MCF-7 cells 5 days after transfection either with scrambled (SCR) or with CIP2A siRNA. C, SA-β-gal staining of MDA-MB-231 cells 5 days after transfection either with siSCR or with siCIP2A. D, Western blot analysis of CIP2A and p21 expression in either control (AdCTL) or CIP2A (AdCIP2A)–transduced (MOI = 40) MCF-7 cells treated with Nutlin-3 (3 μmol/L) for 3 days. Irrelevant data have been removed from the original graph. E, SA-β-gal staining of AdCTL- or AdCIP2A-transduced (MOI = 40) MCF-7 cells treated with Nutlin-3 (3 μmol/L) for 3 days. Shown is mean ± SD from 2 experiments. **, P = 0.0022 by Student t test. F, RT-PCR analysis of cellular senescence–associated p53-regulated genes IFNG, IRF5, IGFBP5, RBL2, and SOD2 from AdCTL- or AdCIP2A-transduced (MOI = 40) MCF-7 cells treated with Nutlin-3 (3 μmol/L) for 3 days. Shown is log2 fold change ± SEM of 2 replicates from a representative experiment of E. H, Western blot analysis of CIP2A, p21 and E2F1 expression in MCF-7 cells treated with doxorubicin (Doxo) with indicated concentrations. I, SA-β-gal staining of AdCTL- or AdCIP2A-transduced (MOI = 40) MCF-7 cells treated with Doxo (2 μmol/L) for 3 days. Shown is mean ± SD of 3 replicates from a representative experiment in I. **, P = 0.0082 by Student t test. A–E, H, and I, representative result of at least 2 independent experiments with similar results.

CIP2A inhibits phosphatase activity of serine/threonine phosphatase PP2A (23, 42). Furthermore, inhibition of 2 regulatory B subunits of PP2A, B55α and B56β, rescues CIP2A depletion–induced effects on colony growth and gene expression (34). As a result, we hypothesized that PP2A holoenzymes consisting of either B55α or B56β subunits could be responsible for dephosphorylation of the serine 364 residue of E2F1 in cancer cells. In fact, inhibition of B55α, but not B56β, resulted in increased phosphorylation of serine 364 in E2F1 (Fig. 4F and Supplementary Fig. S3A). In addition, as with CIP2A overexpression, depletion of B55α rescued E2F1 protein downregulation induced by Nutlin-3 (Fig. 4G). Moreover, this effect was not observed with depletion of B56β (Fig. 4G). Taken together, these results suggest that the positive feedback mechanism from CIP2A to E2F1 is mediated by inhibition of the PP2A complex containing the B55α subunit.
E2F1–CIP2A Feedback Loop Defines Senescence Sensitivity

Downregulation of E2F1 has been reported to induce senescence in a p53-independent manner and to prevent tumorigenesis (19–21). To show that loss of E2F1 results in induction of the senescent phenotype in the cell type studied, E2F1 expression was downregulated in MCF-7 cells by short hairpin RNA (shRNA; shE2F1). E2F1 depletion significantly increased the number of SA-β-gal-positive cells as compared with control cells expressing nontargeted shRNA (shNTC1) (Fig. 4H and I). Moreover, E2F1 downregulation either by Nutlin-3, or by E2F1 shRNA, mirrored their effectiveness in inducing the senescent phenotype, but Nutlin-3 could not further increase SA-β-gal positivity in E2F1-depleted cells (Fig. 4H and I). These results indicate that E2F1 downregulation is critical for senescence induction by Nutlin-3–elicited p53 reactivation.

Figure 4. Positive feedback loop between CIP2A and E2F1 functions as a barrier for p21-mediated senescence induction. A, Western blot analysis of CIP2A, p53, p21, phosphorylated (serine 807/serine 811) Rb (ppRb) and E2F1 expression in either control (AdCTL) or CIP2A (AdCIP2A) adenovirus-transduced (MOI = 40) MCF-7 cells treated with Nutlin-3 (3 μmol/L) for 8 hours. Irrelevant data have been removed from the original graph. B, RT-PCR analysis of mRNA expression of CIP2A and E2F1 from either control (AdCTL) or CIP2A (AdCIP2A) adenovirus-transduced (MOI = 40) MCF-7 cells (MOI = 40) treated with Nutlin-3 (3 μmol/L) for 8 hours. Shown is mean ± SEM of 2 independent experiments. C, Western blot analysis of phosphorylated serine 364 (pS364)-E2F1, E2F1, and CIP2A expression in either control (AdCTL) or CIP2A (AdCIP2A) adenovirus-transduced (MOI = 40) MCF-7 cells. D, Western blot analysis of CIP2A, p21, and pS364-E2F1 expression in AdCTL- or AdCIP2A-transduced (MOI = 40) MCF-7 cells treated with Nutlin-3 for 24 hours. E, Western blot analysis of p21, CIP2A, and E2F1 expression in either control (AdCTL) or CIP2A (AdCIP2A) adenovirus-transduced (MOI = 40) MCF-7 cells treated with Nutlin-3 (3 μmol/L) for 24 hours. Irrelevant data have been removed from the original graph. F, Western blot analysis of B55α, pS364-E2F1, E2F1, and CIP2A expression in scrambled (SCR), B55α, or B56β siRNA-transfected MCF-7 cells. G, Western blot analysis of p21, E2F1, and CIP2A expression in SCR, B55α, or B56β siRNA-transfected MCF-7 cells treated with Nutlin-3 (3 μmol/L) for 24 hours. H, SA-β-gal staining of either nontargeting shRNA (shNTC) or E2F1-shRNA (shE2F1) stable-expressing MCF-7 cells treated with Nutlin-3 (2 μmol/L) for 3 days. I, percentage of SA-β-gal-stained and morphologically flattened cells in either shNTC or shE2F1-expressing MCF-7 cells treated with Nutlin-3 (2 μmol/L) for 3 days. Shown is mean ± SEM of replicates ± SEM from one representative experiment. **, shNTC control vs. shNTC N3) P = 0.0019, **, (shNTC control vs. shE2F1 control) P = 0.0032, and n.s. P = 0.1358 by Student t test. J, SA-β-gal staining of MDA-MB-231 cells 3 days after transduction with combination of indicated adenoviruses. AdCIP2A and AdCIP2A were transduced at MOI = 80 and Adp21 and AdCIP2A at MOI = 150. K, percentage of SA-β-gal-positive and morphologically flattened MDA-MB-231 cells 3 days after transduction with combination of indicated adenoviruses (I). Shown is mean ± SEM from a representative experiment. **, P = 0.0021 by Student t test. A, C, D-H, and J, representative result of at least 2 independent experiments with similar results.
Recent studies have shown that cellular senescence can also be triggered by either p21 induction or E2F1 inhibition in cells carrying mutant p53 (4, 19, 20, 43). In contrast, we show here that p21 overexpression downregulates E2F1 and CIP2A expression in p53-mutant MDA-MB-231 cells, in which CIP2A depletion provokes senescence induction (Figs. 2F and 3C). To study whether CIP2A downregulation is required for senescence induced by p21, CIP2A adenovirus-infected MDA-MB-231 cells were reinfected with either control or p21-expressing adenovirus. As shown in Fig. 4J and K, stable expression of CIP2A rescued the senescence phenotype induced by p21 overexpression. Moreover, inhibition of Rb had no effect on CIP2A depletion–induced senescence in MCF-7 cells (Supplementary Fig. S3B and S3C), further indicating that CIP2A regulates senescence downstream of the p53–p21–Rb pathway.

Taken together, these results reveal the E2F1-CIP2A positive feedback loop and its role in determining cellular senescence induction in breast cancer cell lines. Interestingly, our results suggest that even transient stabilization of E2F1 upon p53 reactivation is sufficient to prevent initiation of senescence. Importantly, the functional role of this newly identified feedback loop is not restricted to p53-induced senescence, but contributes also to senescence induction by p21 in p53-mutant cells.

**CIP2A Inactivation Induces Senescence and Growth Arrest and Restricts Tumorigenesis in a Breast Cancer Mouse Model**

We have recently generated a CIP2A hypomorphic mouse model (CIP2A<sup>Hoz</sup>) using gene trap technology (44). Despite efficient inhibition of CIP2A expression in all examined tissues, CIP2A<sup>Hoz</sup> mice do not show obvious developmental or growth defects (Supplementary Fig. S4A–S4G; ref. 44). However, consistent with the senescence phenotype observed in CIP2A-depleted cancer cells (Fig. 3A–C), MEFs isolated from CIP2A<sup>Hoz</sup> mouse embryos (Fig. 5A) underwent growth arrest after only a few passages (Fig. 5B), and displayed increased SA-β-gal staining and flattened cell morphology (Fig. 5C and D). Importantly, Nutlin-3 treatment of WT MEFs induced a level of senescence equal to that observed in CIP2A<sup>Hoz</sup> cells spontaneously, but Nutlin-3 could not further increase senescence in CIP2A<sup>Hoz</sup> cells (Fig. 5D). Moreover, overexpression of CIP2A also rescued Nutlin-3–induced downregulation of E2F1 also in MEFs, indicating that CIP2A-mediated E2F1

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**Figure 5.** Inhibition of CIP2A inhibits growth and induces senescence in MEFs. A, Western blot analysis of CIP2A expression in MEFs isolated from WT and CIP2A gene trap hypomorph (CIP2A<sup>Hoz</sup>) mouse embryos. B, growth curve presenting proliferation capacity of WT and CIP2A<sup>Hoz</sup> MEFs. MEFs from 3 different WT or CIP2A<sup>Hoz</sup> embryos were cultured for 46 days. Two CIP2A<sup>Hoz</sup> MEF colonies ceased to proliferate after first passage, and therefore their flat curves overlap in the graph. C, SA-β-gal staining of WT and CIP2A<sup>Hoz</sup> MEFs at passage 4. Shown is a representative of 2 independent experiments. D, percentage of SA-β-gal–stained WT and CIP2A<sup>Hoz</sup> MEFs treated with Nutlin-3 (10 μmol/L) for 3 days. Shown is mean ± SEM of 2 independent experiments. P values by Student t test. E, Western blot analysis of CIP2A and E2F1 expression in either control (AdCTL) or CIP2A (AdCIP2A) adenovirus-transduced (MOI = 50) WT MEFs. Shown is a representative result of 2 independent experiments.
stabilization is a conserved mechanism between humans and rodents (Fig. 5E).

To study whether, in addition to p53 activation (10), the loss of CIP2A also suppresses tumorigenesis, we analyzed mammary tumor initiation and progression in the MMTV\textsuperscript{neu} breast cancer mouse model crossed with CIP2A\textsuperscript{HOZ} mice. Notably, 35% of MMTV\textsuperscript{neu} tumors are known to harbor mutations in the p53 pathway. Therefore, we used the knockin mouse model, in which 35% of tumors have a p53 loss of function, and the normal MMTV\textsuperscript{neu} mice are used as controls. The average number of mammary tumors per mouse was significantly reduced in CIP2A-deficient mice (Fig. 6D). Furthermore, follow-up of the tumors that developed in mice with both p53 intact and p53 deficient showed that tumors in CIP2A-deficient mice displayed gene expression changes indicative of senescence induction (Fig. 6F). Of
these senescence-inhibiting genes downregulated in new/HOZ tumors (6, 7, 46–48). Twist1 and Id1 are particularly interesting, as they have both recently been shown to block oncogene-driven senescence in breast cancer cells (46, 48). Importantly, expression of the p53-induced senescence marker DcR2 (11) was also increased in CIP2A-deficient new/HOZ tumors at the protein level (Fig. 6H). Moreover, we observed spontaneous induction of SA-β-gal expression in cultured cells isolated from new/HOZ tumors (Fig. 6G and H). Together, these results validate the senescence phenotype of CIP2A-deficient breast cancer cells in vivo.

To confirm the in vivo role for CIP2A in the inhibition of senescence in another setting, and without potentially confounding effects of mouse strain crossings, the effect of CIP2A expression in dimethylbenzanthracene (DMBA) treatment–induced senescence in mouse skin (5) was examined. As hypothesized, we detected significantly more SA-β-gal staining in DMBA-treated CIP2AHOZ mouse skin as compared with WT mouse skin (Supplementary Fig. S4I and S4J). Together, these results validate induction of senescence as a plausible cause for decreased mammary tumorigenesis in CIP2A-deficient mice.

To examine whether the above-described role for CIP2A in promoting E2F1 expression would also be observed in an in vivo setting, we conducted Western blot analysis of tumor lysates. Indeed, E2F1 expression was decreased in new/HOZ tumors as compared with new WT tumors (Fig. 6I and J). In addition, mRNA expression of direct E2F1 target genes, Rbl1 and Id1, was decreased in new/HOZ tumors (Supplementary Fig. S4K).

Taken together, these results provide the first genetic evidence for the requirement of CIP2A for tumor formation and growth. Moreover, these findings validate CIP2A’s functional role as an in vivo inhibitor of senescence induction in breast cancer (Fig. 6B–H).

CIP2A Confers Resistance of Human Breast Tumors to Senescence-Inducing Chemotherapy

Our results thus far have shown that CIP2A expression determines cellular senescence induction in response to p53 and p21 activation. To study the clinical relevance of these findings, the expression levels of, and the prognostic role for, CIP2A were studied in a cohort of breast cancer tumor samples from patients with advanced disease ($n = 1,010$; ref. 49). Interestingly, CIP2A was overexpressed in 79% of the breast cancers in this population of women (Fig. 7A), of whom 89% had axillary node-negative breast cancer and the rest had high-risk node-negative cancer (49). This frequency is far greater than the frequency of CIP2A overexpression in unselected human breast cancers (approximately 40%; Fig. 1B; ref. 22). Also in this cohort, CIP2A expression is significantly associated with high p53 immunopositivity (Fig. 7A) and with several features linked with aggressive disease (Fig. 7A). The difference in overall survival of patients with low or high CIP2A expression did not quite reach statistical significance in the entire patient population ($P = 0.073$; Supplementary Fig. SSA). However, in HER2-negative breast cancers, representing the great majority (77%) of the studied patient material (45), high tumor CIP2A expression was significantly associated with poor overall survival ($P = 0.011$; Fig. 7B) and distant recurrence or death ($P = 0.024$; Supplementary Fig. SSB). In multivariate analysis, assessing the independent role for CIP2A as a prognostic factor in HER2-negative breast cancers, tumor CIP2A expression tended to be associated with poor outcome [$P = 0.058$; for CIP2A− vs. CIP2A+; HR = 4.26; 95% confidence interval (CI), 1.29–14.08; $P = 0.017$; for CIP2A− vs. CIP2A+; HR = 1.54; 95% CI, 0.75–3.15; $P = 0.241$], whereas tumor size (>2.0 cm vs. ≤2.0 cm), axillary nodal status (positive vs. negative), histologic grade (poorly vs. moderately vs. well differentiated), and p53 expression (positive vs. negative) were not associated with survival ($P ≥ 0.10$ for each). However, absent estrogen receptor expression was independently associated with poor survival in HER2-negative breast cancer (HR = 2.18; 95% CI, 1.12–4.23; $P = 0.022$). We speculate that CIP2A does not have prognostic value in HER2-positive cancers ($P = 0.687$; Supplementary Fig. SSC), even though it supports mammary tumorigenesis in the HER2-driven mouse model (Fig. 6E), because human cancers have a more complex pattern of oncoprogenically active proteins, the combined activity of which masks CIP2A’s prognostic effect.

To study the role of tumor CIP2A in the response of HER2-negative cancers to adjuvant therapy, the association of CIP2A expression with survival of patients was studied in patient groups stratified by the type of chemotherapy administered (Fig. 7C). In these groups, patients were randomly assigned to receive either single-agent docetaxel or vinorelbine (3 cycles) followed (in both groups) by 3 cycles of fluorouracil, epirubicin, and cyclophosphamide (FEC; ref. 49). Notably, CIP2A overexpression significantly correlated with poor overall survival in the subgroup of patients who were assigned to receive vinorelbine followed by FEC ($P = 0.019$; Fig. 7D), whereas CIP2A expression was not significantly associated with survival of patients assigned to docetaxel followed by FEC ($P = 0.373$; Supplementary Fig. SSD). Vinorelbine is a semisynthetic vinca alkaloid used to treat several kinds of human cancer, including non–small cell lung cancer and advanced breast cancer (50, 51). Interestingly, another vinca alkaloid, vincristine, has been shown to induce senescence in MCF-7 cells (52). On the basis of this information, and the novel role for the E2F1-CIP2A feedback loop in preventing chemotherapy-induced E2F1 inhibition, we hypothesized that the favorable survival of the patients with CIP2A-negative cancer in the vinorelbine group could be linked with sensitivity of these cancers to vinorelbine-induced inhibition of E2F1. Indeed, vinorelbine-treated MCF-7 cells mimicked the E2F1 and CIP2A inhibition-associated phenotype by displaying increased SA-β-gal positivity and flattened cellular morphology (Fig. 7E). Importantly, induction of a senescence phenotype by vinorelbine was preceded by inhibition of both E2F1 and CIP2A protein expression at the 24-hour time point (Fig. 7F). Interestingly, vinorelbine-induced E2F1 downregulation was not accompanied by either p53 or p21 induction (Fig. 7G and Supplementary Fig. SSE and SSSF), but similarly to Nutlin-3 treatment, it was associated with inhibition of E2F1 mRNA expression (Fig. 7G). To study whether CIP2A-deficient breast cancer cells are indeed more sensitive to vinorelbine-elicited E2F1 inhibition, MCF-7 cells transfected with either scrambled or CIP2A siRNA were treated with vinorelbine for 12 hours, at which time point, vinorelbine did not yet inhibit CIP2A expression in parental cells (Fig. 7H).
E2F1–CIP2A Feedback Loop Defines Senescence Sensitivity

Figure 7. CIP2A confers resistance of human breast tumors to senescence-inducing chemotherapy. A, CIP2A expression in human breast cancer tumors in FinHer study. CIP2A is expressed in 79% of breast tumors and correlates with high p53 immunopositivity and with other poor prognostic factors. P values by χ² test, except for Ki-67 and tumor diameter the Kruskal–Wallis test was used. B, CIP2A expression significantly correlates with survival of patients with HER2-negative tumors. CIP2A−, CIP2A–negative tumor; CIP2A+; moderately CIP2A-positive tumor; CIP2A+++, high CIP2A-expressing tumor. P = 0.011 by log-rank test. C, stratification scheme of patients with HER2-negative tumors to receive therapies including either vinorelbine followed by FEC (n = 340) or docetaxel followed by FEC (n = 343). D, CIP2A overexpression is significantly associated with poor survival of vinorelbine + FEC-treated HER2-negative patients. P = 0.019 by log-rank test. E, SA-β-gal staining of MCF-7 cells treated with vinorelbine (VRB; 30 nmol/L) for 5 days. F, Western blot analysis of E2F1 and CIP2A expression in MCF-7 cells treated with VRB (20 and 30 nmol/L) for 24 hours. G, RT-PCR analysis of p53, p21, E2F1, and CIP2A mRNA expression in MCF-7 cells treated with VRB (20 and 30 nmol/L). H, Western blot analysis of E2F1 and CIP2A expression in either scrambled (scr) or CIP2A siRNA-transfected MCF-7 cells treated with VRB (20 and 30 nmol/L) for 12 hours. Quantitation of E2F1 expression normalized to β-actin expression is shown below the graph. I, Western blot analysis of E2F1 in either control (AdCTL) or CIP2A (AdCIP2A) adenovirus-transduced (MOI = 40) MCF-7 cells treated with VRB (20 and 30 nmol/L) for 12 hours. Quantitation of E2F1 expression normalized to β-actin expression is shown below the graph. J, schematic of the positive feedback loop between E2F1 and CIP2A in regulation of cellular senescence sensitivity downstream of p53. Inactive molecules and functions are shown in gray. In nontransformed cells (left), either oncogene- or chemotherapy-induced p53 activity inhibits E2F1 expression, resulting in subsequent inhibition of CIP2A expression. CIP2A inhibition further inhibits E2F1 protein expression by a posttranslational mechanism involving PP2A. Loss of E2F1–CIP2A positive feedback activity provokes cellular senescence and hence tumor suppression. In tumorigenic cells (right), in which p53 activity is inhibited either by mutations or by enhanced proteolytic degradation, the E2F1–CIP2A positive feedback loop is active, resulting in inhibition of senescence induction and hence tumor progression. Importantly, in addition to p53 inactivation, activity of E2F1–CIP2A feedback may be stimulated by ETS1 and MYC, which enhance CIP2A expression.
As expected, CIP2A siRNA inhibited E2F1 protein expression in nontreated cells, and, importantly, CIP2A deficiency dramatically potentiated E2F1 downregulation in vinorelbine-treated cells (Fig. 7H). Furthermore, exogenous CIP2A expression totally prevented E2F1 downregulation in vinorelbine-treated MCF-7 cells (Fig. 7I).

These results show clinical relevance for CIP2A in the progression and chemotherapy response of human breast cancers. Importantly, these findings imply that CIP2A could be a useful predictive marker for selecting patients with HER2-negative breast cancer, which currently lacks efficient targeted therapy options, for vinca alkaloid-containing chemotherapies. Moreover, these results indicate that the E2F1-CIP2A feedback mechanism is involved in chemotherapy resistance toward compounds that inhibit E2F1 expression independently of p53 or p21 activation.

**DISCUSSION**

Mounting evidence indicates that the tumor suppression function of p53 relies on its capacity to induce senescence (1, 8–10, 53). In this study, we identify inhibition of CIP2A expression as a previously unrecognized mechanism required for senescence induction by activated p53 and p21 (Fig. 7J). CIP2A’s role as a functional p53 target is supported strongly by both unbiased bioinformatics analysis of the transcriptome in CIP2A-depleted cells (Fig. 1K) and by senescence experiments (Figs. 3A, C, E, I, and 5C and D). Importantly, CIP2A is positively regulated by p53 inactivation regardless of whether p53 activity is inhibited by Mdm2 (Fig. 1D and E), by mutations (Fig. 1H), or by RNAi (Fig. 1C). In addition to in vitro conditions, CIP2A expression correlates with p53 mutation in human breast cancer (Figs. 1A and B and 7A), and in vivo reactivation of p53 in transgenic lymphomas expressing p53ER fusion protein potently inhibits CIP2A protein expression (Fig. 1I and J). Furthermore, we show that loss of function E2F1 expression either by genetic mutations or via overexpression of CIP2A. Importantly, our data also indicate that mechanisms other than p53 inactivation–induced E2F1 expression may drive high CIP2A expression in human breast cancer (Figs. 1B and 7A). We postulate that in these cases ETS-1– and MYC-mediated CIP2A expression (24, 30) supports E2F1 protein expression at the posttranslational level in both human and mouse cells. In addition to overexpression data, we also confirmed that CIP2A depletion caused inhibition of E2F1 protein expression (Fig. 7H). In search of a mechanistic explanation for CIP2A-mediated stabilization of E2F1 protein expression, we observed that CIP2A promotes E2F1 serine 364 phosphorylation, and this phosphorylation has been previously shown in another context to be associated with increased stability of E2F1 (17, 41). Moreover, we observed that inhibition of a regulatory subunit of PP2A, B55α, increases E2F1 serine 364 phosphorylation and reverses Nutlin-3-induced downregulation of E2F1 (Fig. 4F and G). Previously, we showed that inhibition of the PPP2R2A gene, encoding B55α, reverses CIP2A depletion–induced antiproliferative and gene expression effects (34). Interestingly, deletion of the B55α gene was recently identified as a potential driver mutation specifically in the luminal B type of breast cancer (55). These results indicate that the B55α-containing PP2A tumor suppressor complex needs to be inhibited during breast cancer progression either by genetic mutations or via overexpression of CIP2A. Importantly, our data also indicate that mechanisms other than p53 inactivation–induced E2F1 expression may drive high CIP2A expression in human breast cancer (Figs. 1B and 7A). We postulate that in these cases ETS-1– and MYC-mediated CIP2A expression (24, 30) supports E2F1 expression and thereby confers on these cells resistance to senescence induction (see Fig. 7 for schematic presentation).

Although CIP2A expression has been shown to predict for poor patient survival in many different human cancer types (refs. 24, 28; Supplementary Table S1), such evidence has thus far been lacking for breast cancer. In this study, we show that CIP2A has a prognostic role in HER2-negative breast cancer, for which novel therapy targets are in high demand. Interestingly, low E2F1 mRNA expression levels were found specifically in HER2-negative breast tumors (56). Therefore, it can be envisioned that the prognostic value of CIP2A becomes more apparent in HER2-negative cancers in which CIP2A-mediated posttranslational increase of E2F1 protein becomes critical for tumor progression. Moreover, the observation that the E2F1 response to senescence-inducing vinorelbine chemotherapy is dependent on CIP2A status provides a plausible mechanistic explanation for the favorable survival of patients who have CIP2A/HER2-negative breast cancer and who were treated with vinorelbine before FEC (Fig. 7D).

Prosenescence therapies are emerging as an alternative approach for cancer treatment (6, 7). However, the majority of the strategies suggested thus far for therapeutic senescence induction rely on activation of p53 and other cellular checkpoint mechanisms (6, 7). Although hypothetically reasonable, these strategies suffer from serious shortcomings because in the majority of human cancers several checkpoint mechanisms are functionally impaired. Therefore, identification of the E2F1–CIP2A–positive feedback
E2F1-CIP2A Feedback Loop Defines Senescence Sensitivity

Antibodies
For immunoblotting, the following antibodies were used: CIP2A: rabbit polyclonal (57) and mouse monoclonal 2G10-3BS (Santa Cruz); p21: rabbit polyclonal C-19 (Santa Cruz); p53: mouse monoclonal DO-1 (Santa Cruz) and rabbit polyclonal CMS (Vector Laboratories); β-actin: mouse monoclonal (Sigma); Rb: rabbit polyclonal C-15 (Santa Cruz); B55ε: mouse monoclonal 2G9 (Cell Signaling); Ser 807/811 phosphorylated Rb: rabbit polyclonal (Santa Cruz); E2F1 KH95: mouse monoclonal (Santa Cruz); serine 364 phosphorylated E2F1: rabbit polyclonal (Abcam); and DcR2: rabbit polyclonal (Abcam).

**Immunohistochemical and Statistical Analysis of Human Breast Cancer Patient Samples**

CIP2A immunostaining in both FinProg and FinHer breast cancer patient cohorts was conducted with polyclonal rabbit antibody (58). CIP2A was immunostained and analyzed from both cohorts of human breast cancer patient tumor samples (FinProg and FinHer studies), as described previously (34). In the FinProg cohort of patients with breast cancer, p53 and Ki-67 immunostaining of breast tumor samples and analysis of tumor size and tumor grades were conducted as previously described (59). In the FinHer cohort of patients with breast cancer, HER2 and Ki-67 immunostaining; analysis of tumor diameter, tumor size, and tumor grade; and statistical analysis of total and cumulative survival and percentage of alive patients in different subgroups were conducted similarly as before (49). The p53 immunostaining from the FinHer cohort was done following same protocol as published for the FinProg study (59). An ethics committee at Helsinki University Hospital (Helsinki, Finland) approved the FinHer study (HUCH 426/E6/00). Regarding FinProg material, permission to use formalin-fixed, paraffin-embedded tissues for research purposes was provided by the Ministry of Social Affairs and Health, Finland (permission 123/08/97).

**Animal Experiments**

**MMTV**<sub>neu</sub> mice (60) expressing oncogenic HER2 under the control of the mouse mammary tumor virus promoter specifically in the mouse mammary gland were purchased from The Jackson Laboratory and crossed with CIP2A heterozygous genetrap hypomorphic mutant mice (CIP2A<sup>het</sup>, ref. 44). MMTV<sup>neu</sup>/CIP2A<sup>het</sup> mice were intercrossed to produce MMTV<sup>neu</sup>/CIP2A<sup>KT</sup>, MMTV<sup>neu</sup>/CIP2A<sup>KT</sup> mice, and MMTV<sup>neu</sup>/CIP2A<sup>L</sup> mice. Mice were genotyped by PCR analysis of genomic DNA for MMTV<sup>neu</sup> transgene according to The Jackson Laboratory's protocol and for CIP2A genetrap, as previously described (44). CIP2A genotyping results were confirmed with mRNA analysis by RT-PCR. Mice were checked for tumor appearance twice a week. Formed tumors were palpated twice a week, and mice were sacrificed when tumor diameter reached 20 mm. Tumor size was measured by palpating and by weighing after preparation of the tumor from sacrificed mice. Immunohistochemical staining for Ki-67 and DcR2 and hematoxylin and eosin (H&E) staining were conducted as previously described (41). Tumor cells were isolated by forcing cells through a 70-μm pore filter (BD Biosciences). Cells were cultured with Dulbecco modified Eagle medium (DMEM)/F12 Ham medium containing 10% serum, insulin, hydrocortisone, and mouse EGF. MEFs were isolated from WT and CIP2A<sup>L</sup> embryos at 13.5 days of gestation, and cultured in DMEM containing 15% serum. In DMBA treatment, the dorsal skin of WT and CIP2A<sup>L</sup> mice was treated with DMBA (20 μg in 200 μL of acetone) 3 times a week for 2 weeks. A day before the first treatment, mouse backs were shaved, and mice were sacrificed 24 hours after the last treatment. Lymphomas lysates from EμMyc/p53ER mice systemically treated with either tamoxifen or peanut oil were prepared as described previously (33). All animal work protocols were approved by the Regional State Administrative Agency for Southern Finland (ESLH-2007-08517, ESLH-2009-00515/Ym-23).

**METHODS**

**Cell Culture and Drug Treatments**

MCF-7, MDA-MB-231, HeLa, and SAOS-2 cell lines were obtained from American Type Culture Collection. HCT116 and its clonal p53 (p53<sup>−/−</sup>) and p21 (p21<sup>−/−</sup>) deletion mutants were kindly provided by Prof. B. Vogelstein (Johns Hopkins University, Baltimore, MD). Cells were tested twice a year for negativity for mycoplasmas and achoplemas with Mycoplasma Detection Kit (Roche). Cells were exposed to the indicated concentrations of Nutlin-3 (Cayman Chemicals), doxorubicin (Sigma), vincristine (Sigma), or RITA (Cayman Chemicals).
Proliferation Assay and SA-β-gal Staining

Proliferation capacity of MEFs was studied by calculating cell numbers of MEFs from 3 different WT and CIP2A<sup>−/−</sup> embryos seeded to 14,000 cells/cm<sup>2</sup> and divided when 70% to 80% confluent. Cells were cultured for 46 days. To detect senescent cells, cells and mouse skin sections were fixed and stained for SA-β-gal at pH 6.0 (Sigma) according to the manufacturer's protocol. Senescent cells in in situ assays were quantified under the microscope by counting morphologically flattened and SA-β-gal-positive cells. SA-β-gal staining in mouse skin was quantified by counting positively stained areas from 2 to 3 sections per mouse.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

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Senescence Sensitivity of Breast Cancer Cells Is Defined by Positive Feedback Loop between CIP2A and E2F1

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