DIMP53-1: A novel small-molecule dual inhibitor of p53-MDM2/X interactions with multifunctional p53-dependent anticancer properties

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Abbreviations: Cellular Thermal Shift Assay, CETSA; Co-immunoprecipitation, Co-IP; dimethyl sulfoxide, DMSO; Microvessel densities, MVD; Murine double minute, MDM; Sulforhodamine B, SRB; Vascular endothelial growth factor, VEGF; Wild-type, wt.

Running title: DIMP53-1: Inhibitor of the p53-MDM2/X interactions

Abstract

The transcription factor p53 plays a crucial role in cancer development and dissemination, and thus p53-targeted therapies are amongst the most encouraging anticancer strategies. In human cancers with wild-type (wt) p53, its inactivation by interaction with murine double minute (MDM)2 and MDMX is a common event. Simultaneous inhibition of the p53 interaction with both MDMs is crucial to restore the tumor suppressor activity of p53. Here we describe the synthesis of the new tryptophanol-derived oxazoloisoindolinone DIMP53-1 and identify its activity as a dual inhibitor of the p53-MDM2/X interactions using a yeast-based assay. DIMP53-1 caused growth inhibition, mediated by p53 stabilization and upregulation of p53 transcriptional targets involved in cell cycle arrest and apoptosis, in wt p53-expressing tumor cells, including MDM2- or MDMX-overexpressing cells. Importantly, DIMP53-1 abolishes the p53-MDM2/X interactions by binding to p53, in human colon

adenocarcinoma HCT116 cells. DIMP53-1 also inhibited the migration and invasion of HCT116 cells, and the migration and tube formation of HMVEC-D endothelial cells. Notably, in human tumor xenograft mice models, DIMP53-1 showed a p53-dependent antitumor activity through induction of apoptosis and inhibition of proliferation and angiogenesis. Finally, no genotoxicity or undesirable toxic effects were observed with DIMP53-1. In conclusion, DIMP53-1 is a novel p53 activator, which potentially binds to p53 inhibiting its interaction with MDM2 and MDMX. Although target-directed, DIMP53-1 has a multifunctional activity, targeting major hallmarks of cancer through its anti-proliferative, pro-apoptotic, anti-angiogenic, anti-invasive and anti-migratory properties. DIMP53-1 is a promising anticancer drug candidate and an encouraging starting point to develop improved derivatives for clinical application.

Introduction

The sequence-specific transcription factor p53 regulates a plethora of genes involved in crucial cellular processes, including cell cycle arrest, cell death, and DNA repair (Hong et al., 2014). Inactivation of the p53 tumor suppressor function is a common event in human cancers with a dramatic impact in tumor development and dissemination (Burgess et al., 2016; Hong et al., 2014; Wade et al., 2013). Although a substantial proportion of cancers harbor wild-type (wt) p53, its function is found inactivated or at least inhibited (Burgess et al., 2016; Wade et al., 2013), mainly by the murine double minute (MDM) proteins, MDM2 and MDMX (or MDM4). Mechanistically, both MDMs bind to p53 inhibiting its transcriptional activity. Additionally, the E3 ligase MDM2 triggers p53 ubiquitin-proteasome

degradation. Although MDMX has no E3 ligase activity, the MDM2-MDMX heterodimer ubiquitinates p53 with higher efficiency than MDM2 homodimers (Burgess et al., 2016; Gomes et al., 2016; Wade et al., 2013). Therefore, both MDMs are powerful oncogenes, commonly overexpressed in several human cancers (Burgess et al., 2016).

Accumulating data demonstrate that wt p53 is a valuable therapeutic target, and that its activation through inhibition of the p53-MDMs interactions is a promising anticancer strategy. Many p53-MDM2 interaction inhibitors have been identified, several of which are currently under clinical trials (Burgess et al., 2016; Gomes et al., 2016; Wade et al., 2013). Nonetheless, given the distinct and cooperative function of both MDMs on p53 inactivation (Burgess et al., 2016; Gomes et al., 2016; Wade et al., 2013), and the resistance of MDMX-overexpressing cells to MDM2-only inhibitors (*e.g.* nutlin-3a) (Li and Lozano, 2013), small-molecules that abrogate the inhibitory effect of both MDMs represent the ideal strategy for full p53 reactivation (Burgess et al., 2016; Gomes et al., 2016; Wade et al., 2013). However, the availability of such compounds is still limited (Graves et al., 2012; Lee et al., 2011; Soares et al., 2015a).

Here, we report the identification of DIMP53-1 as a new p53 activator, which potentially binds to p53 inhibiting its interaction with MDM2 and MDMX. Additionally, DIMP53-1 has *in vitro* and *in vivo* p53-dependent antitumor properties, involving anti-proliferative, pro-apoptotic, anti-angiogenic, anti-invasive and anti-migratory activities.

1. Materials and Methods
1.1. Reagents

Nutlin-3a, SJ-172550, etoposide, cycloheximide, and cyclophosphamide were from Sigma-Aldrich. All tested compounds were dissolved in dimethyl sulfoxide (DMSO; Sigma-Aldrich). Primary antibodies used in Western blot and immunohistochemistry were from Santa Cruz Biotechnology (mouse monoclonal anti-p53, anti-MDM2, anti-BAX, anti-PARP,

anti-PUMA, anti-GAPDH, and rabbit polyclonal anti-p21), Bethyl Laboratories (rabbit

polyclonal anti-MDMX), Invitrogen (mouse monoclonal anti-Pgk1p), Abcam (rabbit

monoclonal anti-Histone H2AX, phospho S139), Pierce Thermo Scientific (mouse

monoclonal anti-VEGF, anti-CD34, and rabbit monoclonal anti-Ki-67). Secondary antibodies

anti-mouse and anti-rabbit horseradish-peroxidase-conjugated were from Santa Cruz

Biotechnology.

1.2. Chemical synthesis of DIMP53-1

Synthesis of DIMP53-1 (Figure 1A) (Pereira et al., 2015; Soares et al., 2016) is described

in Supplementary Material (Scheme S1; Figure S1).

1.3. Yeast-based screening assay

Saccharomyces cerevisiae cells expressing human wt p53 alone or co-expressed with

human MDM2/MDMX were used, as described (Soares et al., 2015a). Briefly, cells were

grown in galactose selective medium with compounds or 0.1% DMSO for 42h; cell growth

was analysed by colony-forming unit counts with the determination of EC_{50} (concentration

that causes 50% of effect) values.

1.4. Human cell lines and growth conditions

Colon adenocarcinoma HCT116 cell lines expressing wt p53 (HCT116p53$^{+/+}$) and its

p53-null isogenic derivative (HCT116p53$^{-/-}$) were provided by Dr. B. Vogelstein (The Johns

Hopkins Kimmel Cancer Center, Baltimore, MD, USA); breast adenocarcinoma MCF-7,

osteosarcoma SJSA-1, and non-tumorigenic breast epithelial MCF10A cell lines (ATCC;

2013); dermal microvascular endothelial HMVEC-D cells (Lonza; 2013). Tumor cells were

cultured in RPMI-1640 with UltraGlutamine (Lonza), supplemented with 10% fetal bovine

serum (FBS; Gibco). MCF10A cells were cultured in DMEM/F-12 supplemented with MEGM SingleQuot Kit Suppl. & Growth Factors (Lonza). HMVEC-D cells were cultured in Endothelial Cell Growth basal medium supplemented with SingleQuots™ Kit (Lonza). Cell lines were maintained in a humidified incubator at 37°C with 5% CO_2.

1.5. Co-immunoprecipitation (co-IP) assay

Co-IP was performed using the Pierce Classic Magnetic IP and Co-IP Kit (Thermo Scientific), as described (Soares et al., 2015a). Detection of p53, MDM2, MDMX and GAPDH was performed by Western blot.

1.6. Sulforhodamine B (SRB) assay

Cell lines were seeded in 96-well plates at the cells/well density of 5.0×10^3 (for HCT116, MCF-7, and SJSA-1), and 1.0×10^4 (for MCF10A and HMVEC-D). Cells were thereafter treated with serial dilutions (1.85-75μM) of DIMP53-1 for 24h and 48h, and its effect on cell proliferation was analyzed by SRB assay (Soares et al., 2015a) with the determination of IC_{50} (concentration that causes 50% of growth inhibition) values. The solvent (DMSO 0.25%) was included as control.

1.7. Cell cycle and apoptosis

HCT116, MCF-7 and SJSA-1 cells were seeded in 6-well plates at 1.5×10^5 cells/well density. Cells were thereafter treated with DIMP53-1 or solvent for 24h. For cell cycle, cells were stained with propidium iodide (PI; Sigma-Aldrich) followed by flow cytometric analysis (Soares et al., 2015a). For apoptosis, cells were analyzed by flow cytometry using the Annexin V-FITC Apoptosis Detection Kit I (BD Biosciences) according to manufacturer's instructions (Soares et al., 2015a).

1.8. RNA extraction and RT-qPCR

Total RNA, from HCT116 cells treated with DIMP53-1 or solvent for 24h, was extracted using the illustra™ RNAspin Mini RNA Isolation Kit (GE Healthcare Life Sciences). 1μg of RNA was used for cDNA synthesis using the M-MuLV reverse transcriptase and RevertAid cDNA Synthesis kit (ThermoFisher) in 20μL final volume, following manufacturer's instructions. RT-qPCR assays were performed in a 384-well plate on a CFX Touch Real-Time PCR Detection System (Bio-rad), starting with 25ng of cDNA (Lion et al., 2013). The 2X KAPA SYBR® FAST qPCR Kit (Kapa Biosystems) and specific primers for *BAX* and *CDKN1A* (p21); Eurofins (MWG), were used; *GAPDH* and *B2M* (reference genes).

1.9. Western blot

HCT116, MCF-7 and SJSA-1 cells were seeded in 6-well plates at 1.5×10^5 cells/well density. After treatment with compounds or solvent, cells were lysed and the protein fractions were analyzed by Western blot, as described (Soares et al., 2015b). Antibodies are described in 2.1.

1.10. Cellular Thermal Shift Assay (CETSA)

To evaluate drug target interactions in cells, the CETSA was performed as described (Tan et al., 2015). Briefly, HCT116p53$^{+/+}$ cells were lysed in appropriate buffer (25mM Tris pH 7.4, 10mM MgCl$_2$, 2mM DTT) by dounce homogenization. HCT116p53$^{+/+}$ cell lysates were incubated with DIMP53-1 or solvent for 1h at room temperature and then heated to the indicated temperatures for 3min, cooled to room temperature for 3min, and placed on ice. Insoluble protein was separated by centrifugation and soluble protein was detected by Western blot. In the experiments at different heating temperatures, the signal intensity was

normalized to the intensity at 25°C (GAPDH denaturation with heating temperatures unable its use as loading control). At a constant temperature (39°C), the increase of non-denatured p53 was calculated setting the signal obtained with DMSO at 39°C as 0, and the signal obtained with DMSO at 25°C (considered the maximum amount of non-denatured p53) as 1.

1.11. *In vitro* migration and invasion assays

Cell migration was analyzed using the wound healing assay and the QCM 24-Well Fluorimetric Chemotaxis Cell Migration Kit (8μm; Merck Millipore), as described (Soares et al., 2016). In the wound healing assay, confluent HCT116p53$^{+/+}$ and HMVEC-D cells, with a wound in the middle of the well, were treated with 3μM DIMP53-1 or solvent. Cells were photographed using the Moticam 5.0MP camera with Motic's AE2000 inverted microscope with 400x magnification at different time-points of treatment until complete closure of the wound. Wound closure was calculated by subtracting the 'wound' area (measured using Image J software) at the indicated time periods after treatment from the initial (0h) 'wound' area. In Chemotaxis Cell Migration Kit, 0.5×10^6 cells/mL of HCT116p53$^{+/+}$ cells were prepared in serum free RPMI 1640 and treated with 3μM of DIMP53-1 or solvent, for 24h. The prepared cell suspensions were distributed in 24-well plates (300μL/insert), followed by addition of 500μL medium containing 10% FBS to the lower chamber. Cells that migrated through the 8μm pore membranes were eluted, lysed and stained with a green-fluorescence dye that binds to cellular nucleic acids. Cell invasion was analyzed using the QCM 24-Well Fluorimetric Cell Invasion Kit (Merck Millipore), according to manufacturer's instructions. This assay consists in the evaluation of the capacity of cell migration through the ECMatrix layer of the upper chamber of the system, and it was performed as Chemotaxis Cell Migration assay, except the incubation time with DIMP53-1 or solvent of 48h. In both assays, the

number of migrated cells was proportional to the fluorescence signal measured using the Bio-Tek Synergy HT plate reader at 480/520nm (ex/em).

1.12. Angiogenesis assay

Endothelial tube formation was evaluated using the *In Vitro* Angiogenesis Assay kit (Millipore) according to manufacturer's instructions. Briefly, 3×10^4 HMVEC-D cells/well were seeded in 24-well plates coated with ECMatrix with DIMP53-1 or solvent for 16h. Cells were photographed (Moticam 5.0MP camera; Motic's AE2000 microscope).

1.13. Comet assay

DNA damage was evaluated in HCT116p53$^{+/+}$ cells, after 48h treatment with 7, 14 and 21μM DIMP53-1, 25μM etoposide (positive control), or solvent, using the OxiSelect Comet Assay kit (Cell Biolabs), according to manufacturer's instructions, with TBE (Tris-borate-EDTA) for electrophoresis. Cells were photographed (Nikon DS-5Mc camera; Nikon Eclipse E400 fluorescence microscope; Nikon ACT-2U software).

1.14. Micronucleus assay

Genotoxicity was analyzed by the cytokinesis-block micronucleus assay in human lymphocytes, as described (Soares et al., 2016). Briefly, fresh peripheral blood samples were collected from healthy volunteers into heparinized vacutainers. Blood samples, suspended in RPMI medium supplemented with 10% FBS, were treated with 7, 14 and 21μM of DIMP53-1, 1μg/mL cyclophosphamide (positive control), or solvent for 44h. Cells were thereafter treated with 3μg/mL cytochalasin B (cytokinesis preventive) for 28h. Lymphocytes were isolated by density gradient separation (Histopaque-1077 and -1119), fixed in 3:1 methanol/glacial acetic acid, and stained with Wright stain. For each sample, 1000

binucleated lymphocytes were blindly scored using a Leica light optical microscope (Wetzlar); the number of micronuclei per 1000 binucleated lymphocytes was recorded.

1.15. *In vivo* antitumor and toxicity assays

Animal experiments were conducted according to the EU Directive 2010/63/EU and to the National Authorities. The BALB/c nude mice and Wistar rats (Charles-River Laboratories) were housed under pathogen free conditions in individual ventilated cages. For toxicity assays, Wistar rats were treated with 50mg/kg DIMP53-1, vehicle (DMSO), or saline solution (control) by intraperitoneal injection, twice a week, during two weeks. After four administrations, blood samples and organs (kidneys, spleen, heart and liver) were collected for toxicological analysis. Each group was composed of four animals. Xenograft tumor assays were performed with HCT116p53$^{+/+}$ and HCT116p53$^{-/-}$ tumor cells. Briefly, 1×10^6 HCT116 cells (in PBS) were inoculated subcutaneously in the mice dorsal flank. Tumor dimensions were assessed by caliper measurement and their volumes were calculated [tumor volume=(L×W^2)/2], where L and W represent the longest and shortest axis of the tumor, respectively. Treatment started when tumors reached approximately 100mm^3 volume (14 days after the grafts). Mice were thereafter treated twice a week with 50mg/kg DIMP53-1 or vehicle by intraperitoneal injection during two weeks. Tumor volumes and body weights were monitored twice a week until the end of the treatment. Animals were sacrificed by cervical dislocation at the end of the study, when tumors reached 1500mm^3, or if the animals presented any signs of morbidity. Each group was composed of six animals.

1.16. Immunohistochemistry

Tumor tissues were fixed in 10% formalin, embedded in paraffin, sectioned at 4μm, and stained with hematoxylin and eosin (H&E) or antibodies, as described (Soares et al., 2016). Briefly, antigen retrieval was performed by boiling the sections for 20min in 10mM citrate buffer (pH 6.0) for staining with all antibodies, except for anti-VEGF for which tissues were treated with 10mM EDTA buffer (pH 8.0). Antibodies are described in 2.1. Immunostaining was carried out using the UltraVision Quanto Detection System HRP DAB kit, from Lab Vision Thermo Scientific, according to manufacturer's instructions. Evaluation of DAB (3,3'-diaminobenzidine) intensity and quantification of marked cells were performed using Image J software. Microvessel densities were determined by counting CD34-positive vessels, as described (Maeda et al., 2007; Weidner et al., 1991).

1.17. TUNEL assay

TUNEL assay was performed using the *In Situ* Cell Death Detection Kit Fluorescein (Roche), according to manufacturer's instructions, as described (Soares et al., 2016).

1.18. Flow cytometric data acquisition and analysis

The Accuri™ C6 flow cytometer and the CellQuest software (BD Biosciences) were used. The FlowJo software was used to identify and quantify cell cycle phases.

1.19. Statistical analysis

Data were statistically analyzed using the GraphPad Prism software. Differences between means were tested for significance using the Student's *t*-test ($*p<0.05$; $**p<0.01$; $***p<0.001$).

2. Results

2.1. Identification of DIMP53-1 as a potential dual inhibitor of the p53-MDM2/X interactions using a yeast-based assay

Derivatives of SLMP53-1, a tryptophanol-derived oxazoloisoindolinone p53 activator (Soares et al., 2016), [International Patent, (Soares et al., 2014)], containing different protective groups in the nitrogen of the indole moiety, were synthesized. The effect of this new chemical library on p53-MDM2 and p53-MDMX interactions was thereafter investigated, using the reported yeast-based screening assay (Soares et al., 2015a). In this assay, the expression of human wt p53 in yeast causes growth arrest that is abolished by human MDM2 or MDMX. The effect of 0.1-50μM compounds was evaluated, and DIMP53-1 (Figure 1A) was identified as a potential dual inhibitor of the p53-MDM2/X interactions (Figure 1B). Nutlin-3a and SJ-172550 were used as positive controls since, as in human cells (Reed et al., 2010; Vassilev et al., 2004), they inhibit the negative effect of MDM2 and MDMX, respectively, having no impact on the other MDM (Figure 1B). Contrary to Nutlin-3a and SJ-172550, DIMP53-1 relieved the negative effect of both MDMs on p53 (Figure 1B). Based on EC_{50} values, DIMP53-1 was less effective than Nutlin-3a on p53-MDM2 interaction, but more effective than SJ-172550 on p53-MDMX interaction (Figure 1C). Additionally, 0.1-50μM DIMP53-1 did not interfere with the growth of control yeast (data not shown), corroborating its selectivity towards the p53-MDM2/X interactions.

The ability of DIMP53-1 to block the p53-MDM2/X interactions in yeast was further demonstrated by co-IP (Figure 1D). Actually, 10 and 20μM DIMP53-1 led to a visible decrease in the amount of MDM2 or MDMX co-immunoprecipitated with p53 in yeast cells co-expressing p53 and MDM2 or MDMX, respectively.

2.2. DIMP53-1 causes p53 stabilization and upregulation of p53 transcriptional targets through potential binding to p53, inhibiting its interaction with MDM2 and MDMX, in human tumor cells

To confirm the molecular mechanism of action of DIMP53-1 as a dual inhibitor of the p53-MDM2/X interactions, its activity was ascertained in p53$^{+/+}$ and p53$^{-/-}$ HCT116 cells. The SRB assay revealed a significant reduction of the DIMP53-1 growth inhibitory effect in the absence of p53, for 24h and 48h treatment (Figure 2A). Despite the selectivity of DIMP53-1 to the p53-pathway, this compound also inhibited the growth of HCT116p53$^{-/-}$ cells. This may indicate an alternative mechanism of action of DIMP53-1 independent of p53, for longer incubation times and higher concentrations of compound.

In HCT116p53$^{+/+}$ cells, 7 and 14μM of DIMP53-1-induced growth inhibition was associated with G0/G1-phase cell cycle arrest (Figure 2B) and apoptosis, as evidenced by the increase of Annexin V-positive cells (Figure 2C) and PARP cleavage (Figure 2E), not observed in p53-null HCT116 cells. Accordingly, 7μM DIMP53-1 upregulated major p53 transcriptional targets, as revealed by the increased *BAX* and *CDKN1A* (p21) mRNA levels (Figure 2D), and MDM2, BAX, PUMA and p21 protein levels (Figure 2E) in p53$^{+/+}$, but not in p53$^{-/-}$, HCT116 cells. Interestingly, in HCT116p53$^{+/+}$ cells, the slight increase of p21 expression levels is in accordance with the modest cell cycle arrest induced by DIMP53-1. Additionally, by cycloheximide treatment to block the protein synthesis, it was confirmed that DIMP53-1 increased the half-life of p53, due to p53 stabilization (Figure 2F).

The ability of DIMP53-1 to block the p53 interaction with MDM2 and MDMX was demonstrated by co-IP, in HCT116p53$^{+/+}$ cells. In fact, DIMP53-1 caused a significant decrease in the amount of MDM2 (at 14μM) and MDMX (at 7 and 14μM) co-immunoprecipitated with p53 (Figures 2G and H). Based on these results, we attempted to identify the potential molecular target to which DIMP53-1 would bind, causing the

abolishment of the p53 interaction with both MDMs. Since DIMP53-1 is a chemical derivative of the previously reported activator of p53, SLMP53-1 (Soares et al., 2016), we hypothesized that DIMP53-1 might bind to p53. To confirm this hypothesis, the potential interaction of DIMP53-1 with p53 was checked by CETSA. In this assay, we analyzed the impact of DIMP53-1 on p53 thermal stabilization, measured by the amount of soluble p53 upon heating. From 39ºC to 42ºC, 10μM DIMP53-1 caused significant p53 thermal stabilization (Figure 3A). Additionally, DIMP53-1 induced a concentration-dependent p53 thermal stabilization, at 39ºC (Figure 3B), reestablishing the levels of non-denatured p53 protein observed at 25ºC in DMSO treated sample. Furthermore, 100μM DIMP53-1 (the highest concentration tested to demonstrate the interaction of DIMP53-1 with p53) did not interfere with MDM2 and MDMX thermal stabilization at different heating temperatures (Supplementary Material, Figure S2).

The growth inhibitory effect of DIMP53-1 was further investigated in human tumor cells expressing wt p53 and overexpressing MDM2 (SJSA-1 cells) or MDMX (MCF-7 cells). In these tumor cells, a noticeable growth inhibitory effect was also obtained with DIMP53-1 (IC_{50} values of 11.8±0.7μM in SJSA-1 and 13.3±0.5μM in MCF-7) (Figure 3C). Moreover, it was shown that both in the MDM2-overexpressing SJSA-1 cells and in the MDMX-overexpressing MCF-7 cells, the growth inhibitory effect of DIMP53-1 (IC_{50}) was mediated by cell cycle arrest (G0/G1- and S-phases in SJSA-1; G0/G1-phase in MCF-7; Figure 3D) and apoptosis, as evidenced by the increase of Annexin V-positive cells (Figure 3E) and PARP cleavage (Figure 3F). Additionally, in both tumor cell lines, DIMP53-1 (IC_{50}) increased the p53 protein levels and upregulated several p53 transcriptional targets, as demonstrated by the increased MDM2, BAX and p21 protein levels (Figure 3F).

Altogether, these results demonstrate that DIMP53-1 is a selective activator of the p53-pathway, abolishing the MDM2 and MDMX inhibitory effect in human tumor cells due to a potential interaction with p53.

2.3.   DIMP53-1 is non-genotoxic in tumor and normal cells, and has low cytotoxicity against normal cells

The genotoxicity of DIMP53-1 was evaluated in tumor and normal cells. In HCT116p53$^{+/+}$ tumor cells, the impact of DIMP53-1 on DNA damage was analyzed by checking comet-positive cells and histone H2AX phosphorylated on serine-139 (γH2AX; phosphorylation of histone H2AX marks the first step in cellular response to DNA double-strand breaks, and its visualization allows the assessment of DNA damage). The results obtained showed that, unlike etoposide (positive control), 7, 14 and 21μM DIMP53-1 did not increase the percentage of comet-positive cells after 48h treatment (Figures 4A and B), or the levels of γH2AX after 12h treatment (Figure 4C). Furthermore, in peripheral lymphocytes of normal individuals, 7, 14 and 21μM DIMP53-1 did not increase the number of micronuclei compared to solvent (Figures 4D and E).

DIMP53-1 cytotoxicity was also checked in normal cells by assessing its growth inhibitory effect on breast epithelial MCF10A cells, through the SRB assay (Figure 4F). The IC$_{50}$ value of DIMP53-1 in these cells was higher than 75μM, supporting its selective cytotoxicity toward tumor cells.

Altogether, DIMP53-1 is non-genotoxic in human tumor and normal cells, and has low cytotoxic effects against human normal cells.

2.4. DIMP53-1 reduces *in vitro* angiogenesis, and tumor cell migration and invasion

The impact of DIMP53-1 on HCT116p53$^{+/+}$ cell migration and invasion was investigated. With such purpose, the concentration of 3μM (IC$_{10}$) of DIMP53-1, which does not significantly interfere with HCT116p53$^{+/+}$ cell growth, was used. In the wound healing assay, 3μM DIMP53-1 significantly inhibited HCT116p53$^{+/+}$ cell migration, and the subsequent wound closure, when compared to solvent (Figures 5A and B). These results were confirmed using the Chemotaxis Cell Migration assay, in which 24h treatment with 3μM DIMP53-1 led to a significant reduction of HCT116p53$^{+/+}$ cell migration compared to solvent (Figure 5C). Additionally, 3μM DIMP53-1 inhibited HCT116p53$^{+/+}$ cell invasion through a Matrigel® matrix, evaluated by the Cell Invasion assay after 48h treatment (Figure 5D).

The anti-angiogenic potential of DIMP53-1 was also investigated. Initially, its anti-proliferative effect on HMVEC-D endothelial cells was assessed, and an IC$_{50}$ higher than 50μM was obtained (data not shown), indicating low toxicity of DIMP53-1 towards endothelial cells. Thereafter, the wound healing assay was performed to evaluate the effect of 14μM DIMP53-1 (IC$_{10}$ value in HMVEC-D) on HMVEC-D cell migration. At this concentration, a significant decrease of endothelial cell migration was observed (Figures 5E and F). Moreover, using an *In Vitro* Angiogenesis Assay, a significant anti-angiogenic effect was observed after 16h treatment with 10 and 14μM DIMP53-1. In fact, DIMP53-1 led to a dose-dependent decrease of HMVEC-D tube formation (Figures 5G and H).

Altogether, DIMP53-1 demonstrates *in vitro* anti-angiogenic, anti-migration, and anti-invasive effects.

2.5. DIMP53-1 has *in vivo* antitumor activity without apparent toxic side effects

To evaluate some primary toxicity signs, 50mg/kg DIMP53-1 was tested in Wistar rats. Following the same administration procedure conducted in tumor xenograft mice models, organs relative weight (trophism), and biochemical and hematological data were analyzed for saline, vehicle and DIMP53-1 groups (Table 1). No differences between the three groups on relative weight of liver, kidneys, heart and spleen were observed. Concerning biochemical data, only a slight decrease of urea in the vehicle group compared to the saline group, and a slight increase of uric acid in the DIMP53-1 group compared to controls (saline and vehicle groups) were observed. These results indicated no apparent liver or kidney toxicity. Regarding hematological data, just a small increase on reticulocyte number was observed in the vehicle group compared to the saline group, with no alterations between DIMP53-1 and the control groups. Overall, no apparent toxic side effects were observed for DIMP53-1 on the tissues most commonly affected by conventional chemotherapeutics.

The *in vivo* antitumor potential of DIMP53-1 was evaluated using human tumor xenograft mice models of p53$^{+/+}$ and p53$^{-/-}$ HCT116 cells. Four intraperitoneal administrations of 50 mg/kg DIMP53-1 inhibited the growth of p53-expressing HCT116 tumor compared to vehicle (Figure 6A). Conversely, for the same conditions, DIMP53-1 did not interfere with the growth of p53-null HCT116 tumors, further reinforcing its p53-dependent antitumor activity (Figure 6A). Furthermore, no significant body weight loss or morbidity signs were observed in DIMP53-1-treated mice compared to vehicle (Figure 6B).

The subsequent analysis of tumor tissues was performed to check *in vivo* p53-dependent antitumor events promoted by DIMP53-1. Proliferation, apoptosis and angiogenesis markers were checked in p53$^{+/+}$ and p53$^{-/-}$ HCT116 tumor tissues by immunohistochemistry and TUNEL staining (Figures 6C-F). In p53-expressing tumor tissues,

DIMP53-1 reduced proliferation (decrease of Ki-67-positive staining) and stimulated apoptosis (increase of BAX expression and DNA fragmentation demonstrated by TUNEL-positive staining), compared to vehicle (Figures 6C-E). To study the angiogenic profile of tumor tissues, the vascular endothelial growth factor (VEGF; angiogenesis inducing factor) and the microvessel density (MVD; determined using the marker of newly formed vessels CD34) were determined. The results obtained revealed lower levels of VEGF, and MVD in p53-expressing tumor tissues treated with DIMP53-1, compared to vehicle (Figures 6C, D and F). Particularly, an overall 5-fold reduction of MVD was observed in p53-expressing tumor tissue treated with DIMP53-1 (Figure 6F). Conversely, no apparent differences in these markers were observed between DIMP53-1 and vehicle in p53-null tumors (Figures 6C-F).

Altogether, these results support an *in vivo* p53-dependent anti-proliferative, pro-apoptotic, and anti-angiogenic activity of DIMP53-1.

3. Discussion

The complexity underlying cancer highlights the need for the development of strategies that would target the intricate cancer network, in order to modulate the different hallmarks of cancer and hence treat cancer as a complex disease. The key role of p53 in cancer hallmarks renders p53-targeted anticancer therapies highly encouraging. Actually, an effective inhibition of cancer development and progression has been achieved with strategies devised to rectify a dysfunctional p53 pathway, particularly due to MDM2 and MDMX overexpression (Hong et al., 2014; Li and Lozano, 2013; Wade et al., 2013). Consistently, the dual inhibition of the p53-MDM2/X interactions, for full p53 reactivation, has gained strength to treat wt p53-expressing tumors, particularly MDMX-overexpressing tumors commonly resistant to only MDM2-inhibitors (Burgess et al., 2016; Li and Lozano, 2013).

Here we report a novel tryptophanol-derived oxazoloisoindolinone, DIMP53-1, identified as a new dual inhibitor of the p53-MDM2/X interactions. The molecular mechanism of action of DIMP53-1, identified in yeast, was validated in human tumor cells with and without p53. In fact, DIMP53-1 caused tumor cell growth inhibition mediated by p53 stabilization and upregulation of p53 transcriptional targets involved in cell cycle arrest and apoptosis, in wt p53-expressing tumor cells, including MDM2- or MDMX-overexpressing cells. Notably, DIMP53-1 abolished the p53-MDM2/X interactions by potentially binding to p53 in human tumor cells.

The loss of p53 function has been related to the development of a metastatic phenotype (Powell et al., 2014), the most frequent cause of mortality in cancer patients (Cordani et al., 2016; Spano et al., 2012). Actually, p53 stimulates the transcription of repressors of cell migration and invasion (Powell et al., 2014). It is therefore expected that the restoration of p53 function may suppress cancer dissemination. Thus an effective anti-migratory and anti-invasive activity of DIMP53-1 was demonstrated in wt p53-expressing tumor cells.

Angiogenesis is a major hallmark of cancer since proliferation and metastatic spread of cancer cells depend on the adequate supply of oxygen and nutrients (Baeriswyl and Christofori, 2009). Actually, several anti-angiogenic agents have been explored in cancer treatment, particularly in combination with conventional chemotherapeutic agents (Vasudev and Reynolds, 2014). The p53 activity has been negatively correlated with this process through indirect inhibition of key proteins, such as VEGF. Particularly, it was demonstrated that p53 indirectly represses VEGF expression by inhibiting transcription factors such as SP1 and E2F (Pal et al., 2001; Qin et al., 2006). Here, the therapeutic potential of DIMP53-1 was further reinforced through confirmation of *in vivo* anti-angiogenic activity through depletion of VEGF in tumors. Interestingly, despite the anti-angiogenic activity of DIMP53-1 in an *in*

vitro endothelial cell system (without tumor cells), the results obtained *in vivo* showed that this anti-angiogenic effect is highly dependent on tumor environment, particularly of the p53 status in these tumors. In fact, the anti-angiogenic activity of DIMP53-1 was abolished in p53-null tumor xenografts. These results emphasize a strong connection between the activation of the p53-pathway by DIMP53-1 and its anti-angiogenic activity in tumors. Further studies are required to clarify the molecular pathways involved in DIMP53-1 anti-angiogenic activity.

Additionally, DIMP53-1 is non-genotoxic in both normal and tumor cells, and presents no significant toxicity both in normal cells and in rats. Most importantly, in human tumor xenograft mice models, a p53-dependent antitumor activity of DIMP53-1 was observed. Actually, DIMP53-1 suppressed the growth of wt p53-expressing tumors, through inhibition of proliferation and induction of apoptosis, without interfering with the growth of p53-null tumor xenografts.

Interestingly, to date, only the furan derivative RITA was reported as a small-molecule inhibitor of the p53-MDM2 interaction by binding to p53 instead of MDM2 (Gomes et al., 2016; Hong et al., 2014; Wade et al., 2013). However, conversely to RITA, DIMP53-1 has non-genotoxic effects, also acts on the p53-MDMX interaction, and exhibits selectivity to the p53-pathway, particularly highlighted in *in vivo* mice models.

4. Conclusions

This work reports the identification of a new p53 ligand, which activates the p53 function through abolishment of its interaction with MDM2/X. DIMP53-1 has *in vivo* p53-dependent antitumor properties with no apparent toxic side effects, and exhibits anti-proliferative, pro-apoptotic, anti-angiogenic, anti-invasive and anti-migratory activities. Collectively, although DIMP53-1 is a targeted agent, it also presents a multifunctional activity, interfering with

several hallmarks of cancer. Besides its great promise as an anticancer drug candidate,

DIMP53-1 is also an encouraging starting point for further development of dual inhibitors of

the p53-MDM2/X interactions with improved therapeutic potential for clinical translation.

Authors' contributions

JS performed experiments, analyzed and interpreted the data, and wrote the paper; ME

performed the synthesis and NMR of DIMP53-1; LR, HR, ASG, SG, JBL, AI performed

experiments, analyzed and interpreted the data; FR and CG performed the *in vivo*

experiments; MMMS conceived the design and synthesis of DIMP53-1, analyzed and

interpreted the data; LS conceived the study, analyzed and interpreted the data, and wrote the

manuscript. All authors read and approved the final manuscript.

Disclosure of Potential Conflicts of Interest

The authors declare no competing interest.

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Table 1. **Toxicity studies of DIMP53-1 in Wistar rats.**

	Saline	Vehicle	Treated
Body weight and relative tissue weight (trophism)			
BW (g)	340.30 ± 13.45	361.80 ± 0.01	353.25 ± 3.99
Heart/BW (g/kg)	3.03 ± 0.03	3.01 ± 0.09	3.19 ± 0.12
Liver/BW (g/kg)	38.71 ± 2,36	38.52 ± 0.89	40.72 ± 1.14
Kidney/BW (g/kg)	7.08 ± 0.40	6.81 ± 0.27	6.96 ± 0.32
Spleen (g/kg)	2.10 ± 0.20	2.15 ± 0.12	2.07 ± 0.20
Biochemical data			
Blood Glucose(mg/dL)	188.0 ± 7.51	207.20 ± 7.00	242.25 ± 25.68
Urea (mg/dL)	20.67 ± 0.77	18.34 ± 0.24*	19.10 ± 0.62
Uric acid (mg/dL)	1.07 ± 0.07	0.82 ± 0.10	4.10 ± 0.50*
Creatinine (mg/dL)	0.30 ± 0.00	0.30 ± 0.01	0.36 ± 0.03
Total Proteins (g/dL)	5.50 ± 0.00	5.35 ± 0.17	6.38 ± 0.40
Albumin (g/dL)	3.03 ± 0.03	2.90 ± 0.05	3.13 ± 0.03
ALT (U/L)	36.00 ± 2.89	30.75 ± 3.30	35.00 ± 1.87
AST (U/L)	95.33 ± 25.36	56.25 ± 4.60	115.75 ± 20.89
Total Chol (mg/dL)	44.33 ± 1.76	52.40 ± 3.54	54.00 ± 3.37
Triglycerides (mg/dL)	107.00 ± 16.29	161.40 ± 17.55	229.50 ± 26.70
Hematological data			
RBC count ($x10^6$/μL)	7.10 ± 0.15	7.41 ± 0.28	8.23 ± 0.24
HGB (g/dL)	13.97 ± 0.18	13.95 ± 0.46	14.68 ± 0.28
HCT (%)	40.50 ± 0.82	42.28 ± 2.03	47.85 ± 1.87
WBC counts ($x10^3$/μL)	1.93 ± 0.68	2.15 ± 0.88	1.05 ± 0.26

PLT counts (x10^3/μL)	811.00 ± 29.61	793.80 ± 28.35	726.75 ± 47.43
RET counts (%)	2.80 ± 0.12	3.56 ± 0.23*	3.59 ± 0.31

Data were analyzed for saline, vehicle and 50mg/kg DIMP53-1 (treated) rat groups, after four

intraperitoneal administrations (twice a week). Results are mean±S.E.M. of four independent

experiments; *p<0.05 (comparison was made between saline and vehicle groups, and

between vehicle and treated groups). ALT, alanine aminotransferase; AST, aspartate

aminotransferase; BW, body weight; CK, Creatine Kinase; HCT, hematocrit; HGB,

Hemoglobin concentration; PCT, plateletcrit; PLT, platelet; RBC, red blood cell count; RET,

reticulocytes; WBC, white blood cells.

Figure Legends

Figure 1. Identification of DIMP53-1 as a potential dual inhibitor of the p53-MDM2/X

interactions using yeast. A. DIMP53-1 chemical structure. **B.** Effect of 0.1–50μM DIMP53-

1, Nutlin-3a and SJ-172550 on the reestablishment of p53-induced growth inhibition in

MDM2/MDMX co-expressing yeast, after 42h; results were plotted setting the growth of

DMSO-treated cells expressing p53 alone as 100%; data are mean±SEM of six independent

experiments; values significantly different from DMSO (***p<0.001). **C.** EC$_{50}$ values of

DIMP53-1, Nutlin-3a and SJ-172550 obtained from concentration-response curves presented

in (B). **D.** Co-IP was performed with anti-p53 (IP:p53) or anti-immunoglobulin G (IgG)

antibodies, followed by immunoblotting with anti-MDM2, anti-MDMX, and anti-p53

antibodies in cells treated with 10 and 20μM DIMP53-1 or DMSO for 42h; whole cell lysate

(Input).

Figure 2. DIMP53-1 shows a p53-dependent growth inhibitory effect in human tumor cells mediated by cell cycle arrest, apoptosis, p53 stabilization, upregulation of p53 target genes, and disruption of the p53-MDM2/X interactions. A. Concentration-response growth curves for DIMP53-1 in $p53^{+/+}$ and $p53^{-/-}$ HCT116, after 24h and 48h; data are mean±SEM of four independent experiments; incubation with DMSO, in equivalent % of DIMP53-1, was used to normalize the results. **B and C.** Cell cycle arrest (B) and apoptosis (C) were determined at 7 and 14μM of DIMP53-1 after 24h in $p53^{+/+}$ and $p53^{-/-}$ HCT116 cells; data are mean±SEM of three independent experiments; values significantly different from DMSO (*$p<0.05$; **$p<0.01$; ***$p<0.001$). **D**. mRNA levels of *BAX* and *CDKN1A* (p21) after 24h with 7 and 14μM DIMP53-1 in $p53^{+/+}$ and $p53^{-/-}$ HCT116 cells; fold expression changes are relative to DMSO and correspond to mean±SEM of three independent experiments. **E.** Western blot analysis was performed after 24h (MDM2, p53) and 48h (PARP, BAX, PUMA, p21) with 7μM DIMP53-1 or DMSO in $p53^{+/+}$ and $p53^{-/-}$ HCT116 cells. **F.** p53 protein levels in HCT116$p53^{+/+}$ cells treated for 24h with DIMP53-1 or solvent followed with cycloheximide (CHX; 150 μg/mL). **G.** Co-IP was performed with anti-p53 (IP:p53) or anti-immunoglobulin G (IgG) antibodies, followed by immunoblotting with anti-MDM2, anti-MDMX and anti-p53 antibodies in HCT116$p53^{+/+}$ cells treated with 7 and 14μM DIMP53-1 or DMSO for 8h; whole cell lysate (Input); in IP:p53 of MDM2, the cut top band corresponds to the anti-p53 antibody, and the other two bands correspond to MDM2 isoforms. **H.** Quantification of IP:p53 immunoblots; data are mean±SEM of three independent experiments; values significantly different from DMSO (*$p<0.05$; **$p<0.01$; ***$p<0.001$). In (E), (F) and (G), immunoblots are representative of three independent experiments; GAPDH (loading control).

Figure 3. DIMP53-1 potentially binds to p53 and inhibits the growth of MDM2- and MDMX-overexpressing tumor cells through induction of cell cycle arrest, apoptosis, and upregulation of p53 target genes. A and B. CETSA experiments were performed in HCT116p53$^{+/+}$ cell lysates in the presence or absence of DIMP53-1. In (A), 10 μM DIMP53-1 was used and lysate samples were heated at different temperatures; plot represents the signal intensity normalized to the intensity at 25°C. In (B), lysate samples were treated with increasing DIMP53-1 concentrations and heated at 39ºC; plot represents the increase of non-denatured p53 calculated setting the signal obtained with DMSO at 39°C as 0, and the signal obtained with DMSO at 25°C (considered the maximum amount of non-denatured p53) as 1. Results are mean±SEM of three independent experiments. **C.** DIMP53-1 concentration-response growth curves in SJSA-1 and MCF-7 cells, after 48h; data are mean±SEM of four independent experiments; incubation with DMSO, in equivalent % of DIMP53-1, was used to normalize the results . **D and E.** Cell cycle arrest (D) and apoptosis (E) were determined in SJSA-1 and MCF-7 cells at IC$_{50}$ and $2 \times$IC$_{50}$ ($2 \times$DIMP53-1) concentrations, after 24h; data are mean±SEM of three independent experiments; values significantly different from DMSO (*p<0.05; **p<0.01; ***p<0.001). **F.** Western blot analysis was performed in SJSA-1 and MCF-7 cells, after 24h (p21) and 48h (PARP, p53, MDM2, BAX) with the IC$_{50}$ of DIMP53-1 or DMSO. In (A), (B), and (F), immunoblots are representative of three independent experiments; in (B) and (F), GAPDH (loading control).

Figure 4. DIMP53-1 is non-genotoxic in normal and tumor cells, and has low cytotoxicity against normal cells. A-C. DNA damage was measured in HCT116p53$^{+/+}$ cells by comet assay (A and B) and by analysis of γH2AX expression levels (C) after treatment with etoposide (ETOP; positive control) or DIMP53-1. In (A), scale bar=20μm; Magnification=200×. In (B), quantification of comet-positive cells (containing more than 5%

of DNA in the tail; assessed by Open Comet/ImageJ); one hundred cells were analyzed in each group. In (C), γH2AX levels were determined by Western blot; immunoblots are representative of three independent experiments; GAPDH (loading control). **D and E.** Genotoxicity of 7, 14 and 21μM DIMP53-1 by cytokinesis-block micronucleus (MN) assay after 72h in human lymphocyte cells; 5μg/mL cyclophosphamide (CP; positive control). In (D), scale bar=20μm; Magnification=1000×. In (E), the number of MN per 1000 binucleated lymphocytes was recorded. **F.** DIMP53-1 concentration-response growth curve in MCF10A cells, after 48h; incubation with DMSO, in equivalent % of DIMP53-1, was used to normalize the results. In (B), (E) and (F), data are mean±SEM of three to four independent experiments; in (B) and (E), values significantly different from DMSO (**$p < 0.01$; ***$p < 0.001$).

Figure 5. DIMP53-1 prevents *in vitro* angiogenesis, and tumor cell invasion and migration. A and B. HCT116p53$^{+/+}$ confluent cells treated with 3μM DIMP53-1 or DMSO were observed at different time-points in the wound healing assay. **B.** Quantification of wound-closure of HCT116p53$^{+/+}$ cells in five randomly selected microscopic fields. **C.** Effect of 3μM DIMP53-1 on the migration of HCT116p53$^{+/+}$ cells for 24h, analyzed by the chemotaxis assay. **D.** Effect of 3μM DIMP53-1 on the invasion of HCT116p53$^{+/+}$ cells for 48h, analyzed by cell invasion assay. In (C) and (D), migratory cells were quantified by fluorescence signal; fold changes are relative to DMSO and correspond to mean±SEM of three independent experiments. **E and F.** HMVEC-D endothelial confluent cells treated with 14μM DIMP53-1 or DMSO were observed at different time-points in the wound healing assay. In (F), quantification of wound-closure of HMVEC-D endothelial in five randomly selected microscopic fields. **G.** Anti-angiogenic effect of 10 and 14μM DIMP53-1 was evaluated in HMVEC-D cells for 16h by the endothelial cell tube formation assay. **H.**

Quantification of tube-like structures in five randomly selected microscopic fields; fold changes are relative to DMSO and correspond to mean±SEM of three independent experiments. In (A), (E) and (G), scale bar=5μm and magnification=100×. In (B), (C), (D), (F) and (H), values significantly different from DMSO (**$p<0.01$; ***$p<0.001$).

Figure 6. DIMP53-1 has *in vivo* p53-dependent antitumor activity by inducing apoptosis and inhibiting proliferation and angiogenesis. BALB/c nude mice with about 10 weeks were inoculated subcutaneously, in the dorsal flank, with HCT116p53$^{+/+}$ and HCT116p53$^{-/-}$ tumor cells; when tumors reached approximately 100mm^3 volume (14 days after the grafts), mice were treated twice a week with 50mg/kg DIMP53-1 or vehicle (control) by intraperitoneal injection during two weeks. **A.** Tumor volume growth curves of mice carrying p53$^{+/+}$ or p53$^{-/-}$ HCT116 xenografts treated with DIMP53-1 or vehicle; data are mean±SEM of the tumor volume fold change to the start of treatment. **B.** Mice body weight during treatment with DIMP53-1 or vehicle; values not significantly different from vehicle ($p>0.05$). **C.** Representative images of Ki-67, BAX, DNA fragmentation (TUNEL), CD34 and VEGF detection in p53$^{+/+}$ and p53$^{-/-}$ HCT116 xenograft tumor tissues treated with DIMP53-1 or vehicle at the end of treatment (Scale bar=5μm; Magnification=400x); H&E (Hematoxylin and Eosin). **D-F.** Quantification of immunohistochemistry of p53$^{+/+}$ and p53$^{-/-}$ HCT116 xenograft tumor tissues treated with DIMP53-1 or vehicle. In (D), BAX and VEGF staining quantification by evaluation of DAB (3,3'-diaminobenzidine) intensity. In (E), quantification of the number of positive and negative Ki-67 and TUNEL cells. In (F), evaluation of microvessel density by quantification of vessels stained with anti-CD34; data are mean±SEM of the number of vessels/mm^2 fold change to the vehicle. In (A), (D), (E), and (F), values significantly different from vehicle (*$p<0.05$**; $p<0.01$; ***$p<0.001$).

Supplementary Information

Supplementary Scheme S1. Synthesis of DIMP53-1.

Supplementary Figure S1. ^{1}H NMR and ^{13}C NMR data for compound DIMP53-1.

Supplementary Figure S2. CETSA experiments of MDM2 and MDMX.

A

DMSO ETOP 25μM DIMP53-1 7μM DIMP53-1 14μM DIMP53-1 21μM

B

% of comet-positive cells

*** (ETOP)

DMSO ETOP 7 14 21
DIMP53-1 (μM)

C

DMSO DIMP53-1 (μM) ETOP (100μM)
        7 14 21   kDa

γH2AX   17

GAPDH   37

D

DMSO CP

DIMP53-1
7μM 14μM 21μM

E

MN/1000 lymphocytes

** (CP)

DMSO CP 7 14 21
DIMP53-1 (μM)

F

Cell growth (% of control)

[DIMP53-1] μM