Inhibition of Topo I stabilizes telomere damage

DNA damage persistence as determinant of tumor sensitivity to the combination of Topo I inhibitors and telomere-targeting agents

Annamaria Biroccio¹,*, Manuela Porru¹, Angela Rizzo¹, Erica Salvati¹, Carmen D’Angelo¹, Augusto Orlandi², Daniela Passeri², Marco Franceschin³, Malcolm F.G. Stevens⁴, Eric Gilson⁵, Giovanni Beretta⁶, Gabriella Zupi¹, Claudio Pisano⁷, Franco Zunino⁶, and Carlo Leonetti¹.∗

¹Experimental Chemotherapy Laboratory, Regina Elena Cancer Institute, Rome, Italy; ²Anatomic Pathology Institute, Tor Vergata University, Rome; ³Department of Chemistry, La Sapienza University, Rome; ⁴School of Pharmacy, the University of Nottingham, Nottingham, UK; ⁵Laboratory of Biology and Pathology of Genomes of University of Nice Sophia-Antipolis, CNRS UMR6267/INSERM U998, Faculty of Medicine and Department of Medical Genetics, CHU of Nice, France; ⁶Department of Experimental Oncology and Molecular Medicine, Fondazione IRCCS, Istituto Nazionale Tumori, Milan, Italy; ⁷Sigma-Tau, Pomezia, Italy.

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*Corresponding author: Dr. Annamaria Biroccio and Dr. Carlo Leonetti, Experimental Chemotherapy Laboratory, Regina Elena Cancer Institute, Via delle Messi d’Oro 156, 00158 Roma, Italy. Phone: +39-06-52662534-59. Fax: +39-06-52662592. E-mail: biroccio@ifo.it; leonetti@ifo.it.
Statement of Translational Relevance

Telomere pathway is a well-validated target at the preclinical level, encouraging the evaluation of therapeutic combined option in future clinical protocols. In this context, we have recently reported a specific link between the telomere-targeting agent RHPS4 and chemosensitivity toward camptothecins in colorectal tumors.

The present study strongly supports the use of this combination in cancer therapy by demonstrating a synergistic effect between telomere-targeting agents and novel clinical-relevant camptothecins, having antitumor activity in a large panel of human tumors and favorable pharmacodynamic and pharmacokinetics properties.

We also showed that stabilization of DNA damage, evaluated by induction and persistence of $\gamma$H2AX foci, is a key determinant in the sensitivity to this combination therapy. In conclusion our results show an improvement of the therapeutic efficacy of Topo I inhibitors in combination with G4 ligands and identify $\gamma$H2AX formation as a useful biomarker for monitoring the efficacy of this combination in future clinical applications.
Abstract

**Purpose.** We previously reported that the G-quadruplex (G4) ligand RHPS4 potentiates the antitumor activity of camptothecins both *in vitro* and in tumor xenografts. The present study aims at investigating the mechanisms involved in this specific drug interaction.

**Experimental Design.** Combination index test was used to evaluate the interaction between G4 ligands and standard or novel Topo I inhibitors. Chromatin immunoprecipitation was performed to study the presence at telomeres of various types of topoisomerase, while immunolabeling experiments were performed to measure the activation of DNA damage both *in vitro* and in tumor xenografts.

**Results.** We report that integration of the Topo I inhibitor SN-38, but not the Topo II poison doxorubicin with telomere-based therapy is strongly effective and the sequence of drug administration is critical in determining the synergistic interaction, impairing the cell ability to recover from drug-induced cytotoxicity. The synergistic effect of this combination was also observed by using novel camptothecins and, more interestingly, mice treated with ST1481/RHPS4 combination showed an inhibition and delay of tumor growth as well as an increased survival. The study of the mechanism(s) revealed that treatment with G4 ligands increased Topo I at the telomeres and the functional relevance of this observation was directly assessed by showing that standard and novel camptothecins stabilized DNA damage both *in vitro* and in xenografts.

**Conclusions.** Our results demonstrate an outstanding efficacy of Topo I inhibitors/G4 ligands combination, which likely reflects an enhanced and persistent activation of DNA damage response as a critical determinant of the therapeutic improvement.
Introduction

Guanine-rich stretches of DNA have a high propensity to self-associate into planar guanine quartets to give unusual structures (1) called G-quadruplexes (G4). Quadruplexes are thought to play important roles in some biological events because many guanine-rich regulative regions in the human genome possess the potential to adopt a quadruplex conformation. The conformations of G4 provide selective recognition sites for small molecules and thus these structures have become important drug-design targets for the treatment of various human disorders. Two drugs acting on nucleolin that either target a G4 (CX-3543 or Quarfloxin) or fold into a G4 structure (AS1411) are in Phase II clinical trials against cancer (2,3).

The specific nucleoprotein structure encountered at telomeres controls the terminal replication of chromosomal DNA and protects from the DNA damage checkpoint machinery and repair (4, 5). Telomeric DNA is composed of the repetition of a small G-rich motif (TTAGGG in human cells), ends as a single stranded tail on the 3’-oriented strand (G-tail) and is transcribed into a UUAGGG repeats containing RNA called TERRA (6). Telomeric DNA can fold into non-canonical structures such as t-loops (7) and G4 DNA (8). Both in vitro and in vivo data strongly support the physiological relevance of telomeric G4 DNA (8). An unfolded 3’ overhang is required for an optimal telomerase reaction and G4 formation has been shown to inhibit telomere elongation in vitro (9).

In human cells, the complete replication of telomeric DNA usually depends on telomerase, a specialized reverse transcriptase that uses its RNA template to add G-rich telomeric repeats to the terminal 3’ overhang (10). In preclinical studies, telomerase inhibitors have shown promise as effective antitumor agents against a variety of human tumors. These translational advances have resulted in the first antitelomerase agent, the oligonucleotide-based GRN163L targeting the telomerase RNA template, completing Phase I/II clinical studies (11).
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The inability of telomerase to utilize a G4 folded telomeric substrate has led to the emergence of a novel strategy for cancer therapy. G4-interacting agents are small molecules able to bind and stabilize the telomeric DNA in a quadruplex conformation, thereby inhibiting telomere extension by telomerase (12). Interestingly, G4-interacting compounds might disrupt telomere architecture, both in telomerase- and ALT-positive tumors, causing immediate and profound effects on cell proliferation (13). Over the past decade, many chemical classes of G4 ligands have been described. Several of them reduce the growth of various cancer cell lines in vitro, often accompanied by cellular senescence and/or apoptosis, and can be considered as telomere-damage inducers as evidenced by the characteristic DNA damage response (i.e., the appearance of γH2AX foci) at the telomeres. Moreover, some of them exhibit antitumoral activity in mice bearing various human tumor xenografts (14-17). It is encouraging for future clinical applications that several G4 ligands show in vivo synergistic activity with some conventional cytotoxic agents (18-21).

RHPS4 (3,11-difluoro-6,8,13-trimethyl-8H-quino[4,3,2-kl]acridinium methosulfate) is one of the most effective and selective G4 ligands. Our previous studies revealed that this agent, by stabilizing G4 DNA at telomeres, impairs fork progression and/or telomere processing resulting in telomere damages (16, 22). Telomere dysfunction is the major cause of RHPS4 toxicity since POT1 or TRF2 overexpression is sufficient to overcome the deleterious effects of RHPS4 on cellular proliferation and DNA damage (16). In agreement with the view that the telomere specific effects of RHPS4 is due to G4 stabilization, RHPS4 selectivity binds to quadruplex vs duplex DNA (23). Interestingly in view of clinical application, RHPS4 is active in vivo as a single agent with a good toxicological profile (16, 20).

Telomeric binding proteins facilitate the relief of the topological stress occurring during the progression of the replication fork (24), suggesting that drugs that inhibit topoisomerase
activity, which are widely used in the therapy of different types of cancer, might synergize with anti-telomere strategies. Camptothecins are Topoisomerase I (Topo I) inhibitor chemotherapeutic agents and analogs such as irinotecan and topotecan are approved for treatment of many types of solid tumors such as lung, colorectal, ovarian, cervical and gastric carcinomas. Unfortunately they are not curative as single agents. To improve the efficacy of Topo I inhibitors several approaches could be pursued including development of new camptothecins with a more favorable therapeutic profile and their combination with other cytotoxic agents and/or molecularly targeted agents, on the basis of the knowledge of the mechanisms of tumor cells response (25). The convergence of these efforts could result in more effective anticancer therapies.

In this context, we recently reported that antitumor efficacy of camptothecins is increased when used in combination with the G4 ligand RHPS4 (20). On the basis of these results, the aim of the present study was to investigate the mechanism(s) involved in this specific drug interaction by using well-characterized G4 ligands and standard or novel Topo I inhibitors (26-29).
Materials and Methods

Drugs. 7-ethyl-10-hydroxycamptothecin (SN-38, Alexis, Florence, Italy) and adriamycin (Adriblastina, Pharmacia, Milan, Italy) were used. ST1481 (Gimatecan), ST1968 (Namitecan) camptothecins (30, 31) were provided by Sigma-Tau (Pomezia, Italy). IDN5174 was supplied by INDENA (Milan, Italy). The G4 ligands RHPS4, CORON and PIP-PIPER(1,7), were synthesized as previously described (23, 32).

Cell lines and culture conditions.

BJ fibroblasts expressing hTERT and SV40 early region (BJ-HELT) were maintained as previously described (33). HT29 and HCT116 colorectal adenocarcinoma cells were obtained and maintained as previously reported (20).

Cytotoxic assay

Cells were seeded at a density of $5 \times 10^4$ cells/plate and exposed 24 hrs later to the following drugs: RHPS4 (0.5-2 $\mu$M for 96 hrs); CORON (0.01-0.1 $\mu$M for 96 hrs); PIP-PIPER(1,7) (1-10 $\mu$M for 96 hrs); SN-38 (0.5-2 $\mu$M for 2 hrs); ST1481 (0.01-0.1 $\mu$M for 2 hrs); IDN5174 (0.5-10 $\mu$M for 2 hrs) and ST1968 (0.1-5 $\mu$M for 2 hrs). In the combination experiments, the medium containing the first drug was removed and replaced with fresh medium containing the second drug. Colony forming ability was evaluated as previously reported (34).

Chromatin Immunoprecipitation assay (ChIP)

BJ-HELT fibroblasts were treated for 24 hrs with 0.5 $\mu$M RHPS4, 0.05 $\mu$M CORON and 4 $\mu$M PIP-PIPER(1,7), or for 2 hrs with 0.5 $\mu$M SN-38. ChIP assay was performed as previously described (16). The following antibodies were used: pAbs anti-Topo I, Topo II$\alpha$ and Topo III$\alpha$ (Abcam Ltd.; Cambridge UK). mAb anti-\(\beta\)-actin (Sigma, Chemicals, Milano, Italy) was used as negative control of the ChIP assay.

Immunofluorescence analysis
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BJ-HELT fibroblasts were treated with 0.5 μM SN-38 for 2 hrs and 0.5 μM RHPS4 for 48 hrs alone or in combination. Cells were processed for IF as previously reported (22) using the following antibodies: mAb anti-γH2AX (Upstate, Lake Placid, NY) and pAb anti-TRF1 (Abcam). To estimate the percentage of γH2AX-positive cells and the percentage of cells containing at least four γH2AX /TRF1 colocalization (TIF=Telomere-dysfunction-Induced Foci), at least 200 nuclei or 50 nuclei for each sample, respectively, were scored.

**Cell cycle analysis and apoptosis**

Cell cycle analysis was performed by flow cytometry (Becton-Dickinson, Heidelberg, Germany) as previously reported (34). Apoptotic cells were scored by Hoechst staining.

**Antitumor activity**

CD-1 male nude (nu/nu) mice, 6-8 weeks old were purchased from Charles River Laboratories (Calco, Italy). All procedures involving animals and their care were conducted as previously reported (35). RHPS4 was given i.v. at 10 mg/Kg/d for fifteen consecutive days and ST1481 was administered per os at 1.5 mg/kg q4dx4 times, based on previous results (20, 36). In particular, nude mice were injected with HT29 at 3 x 10⁶ cells/mice and treatments were started when a tumor mass of about 600 mg was evident in the mice. In the combination experiments the two drugs were administered with an interval of 24 hrs. The tumor weight was calculated from caliper measurements (37) and antitumor efficacy of treatments was assessed as previously reported (20).

**Immunohistochemical analysis**

Activation of damage response was determined immunohistochemically by using mAb anti-γH2AX (Upstate) as previously reported (16). The number of γH2AX-positive cells were counted in eight high-power fields (400x magnification) per section and reported as γH2AX-positive nuclei/mm². Two independent observers did the counts in blinded fashion.

**Statistical analysis.**
Synergism, additivity, and antagonism were assessed by isobologram analysis using the Chou-Talalay method as previously described (20). Combination index (CI) values <0.9, >0.9 < 1.2, and >1.2 indicate synergism, additive effect, and antagonism, respectively. Student’s t test (unpaired, two-tailed) was used for statistical comparison of differences. Survival curves of mice were generated by Kaplan-Maier product-limit estimate, and statistical differences between the various groups were evaluated by log-rank analysis with Yates correction (software Primer of Biostatistics; McGraw-Hill, New York, NY). Differences were considered statistically significant when p<0.05.
Results

The Topo I inhibitor SN-38 and telomere-targeting agents in combination have a strong synergistic effect

Previous data of combined treatment between the G4 ligand RHPS4 and a classic topoisomerase inhibitor revealed a good synergism between these compounds both in vitro and in xenografts (ref. 20 and Figure 1A). The present study aims at investigating the mechanisms involved in this specific interaction. Firstly, we evaluated the efficacy of SN-38 with well-established telomere targeting agents. The exposure of HT29 colon carcinoma cells to the combination of SN-38 and the G4 compounds RHPS4, CORON and PIP-PIPER(1,7) strongly reduced cell survival (Figure 1A). These results reported in terms of Combination Index (CI) showed a synergistic interaction (as documented by CI values less than 0.1), when cells were treated with SN-38 followed by G4 ligands (Figure 1B). The sequence-dependent effect of this combination was highlighted by a slight additive or antagonistic effect observed by treating the cells with the opposite sequence of drug treatment (Figure 1B). The positive interaction between SN-38 and telomere-targeting agents seems to be specific for the Topo I inhibitor, since the combination with the Topo II inhibitor doxorubicin did not show a marked increase of cytotoxic activity and the effect was almost additive or antagonist regardless of the G4 ligands and/or the sequence of drug treatment (Figure 1C and D).

Analysis of cell cycle perturbation and cell death strongly supported the sequence-dependent effect of the SN-38/G4 ligands combination. SN-38 alone induced a block of cells in S-phase that was almost recovered at 48 hrs after the end of treatment (Figure 2A). A similar cell cycle profile was observed in the RHPS4→SN-38 combination, demonstrating that the treatment with RHPS4 before the Topo I inhibitor did not impair the ability of cells to recover from drug-induced S-phase arrest (Figure 2A). Interestingly, cells exposed to the SN-38→RHPS4 combination still showed a strong perturbation of cell cycle
Inhibition of Topo I stabilizes telomere damage and a significant amount of cells were in the sub-G₁ compartment (Figure 2A). Quantitative analysis of cell death by Hoechst staining, revealed that about 30% of cells showed apoptotic bodies in the SN-38→RHPS4 combination, percentage that was less of 10% in the opposite sequence as well as in the SN-38 alone (Figure 2B and C). Our results suggest that the sequential combination of SN-38 with G4 ligands impairs the cells to recover from drug-induced cytotoxicity.

**Treatment with G4 ligands increases the amount of Topoisomerase I at telomeres.**

To understand the molecular basis of the positive interaction between a Topo I inhibitor and telomere-targeting agents, we investigated the ability of different G4 ligands to modulate the topoisomerase binding to telomeric DNA. Chromatin Immunoprecipitation assay performed in BJ-EHLT fibroblasts showed an enrichment of Topo I at the telomeric sequences in the samples treated with RHPS4, CORON and PIP-PIPER(1,7) compared to untreated ones. This enrichment was not observed by using the Alu proble (Figure 3A and 3C), thus indicating a specific recruitment of Topo I at telomeres. As control of this result, increased amount of Topo I at both telomeric and Alu sequences was found in cells exposed to the Topo I inhibitor SN-38 (Figure 3B and D).

The binding to telomeric DNA of Topo IIIα, a topoisomerase of Topo I family, was also increased in RHPS4-treated sample (Figure 3A), consistently with the ability of this G4 ligand to activate the helicase BLM (22). In agreement with previous studies (24), we detect the presence of Topo IIα at the telomeres of untreated cells. However, in contrast to Topo I, we do not observed any enrichment of Topo IIα at telomeric regions. We conclude that G4 ligands trigger a DNA damage that specifically requires the Topoisomerase I, providing an explanation for the strong synergistic interaction we observed between G4 ligands and camptothecin.
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Combined treatment of SN-38 and RHPS4 causes a persistent DNA damage

By means of the phosphorylation of H2AX (γH2AX) as a sensitive hallmark of DNA damage, we found that the percentage of γH2AX-positive cells was significantly increased after SN-38 and RHPS4 exposure (Figure 4A). Interestingly, cells treated with SN-38 alone rapidly recovered the damage, the percentage of γH2AX-positive cells decreased from about 70 to 30% at 48 after the end of treatment (Figure 4A). This finding is consistent with the reversibility of the camptothecin-mediated DNA damage. When SN-38 was followed by RHPS4 treatment, cells failed to recover the DNA damage, and the percentage of damaged cells remained significantly higher if compared to that of SN-38 or RHPS4 alone (Figure 4A). Of note, the treatment with RHPS4 before SN-38 did not impair the capacity of cells to recover the damage (Figure 4A), consistently with the observation showing that this sequence of drug exposure did not elicit a synergistic interaction (ref. 20 and this paper). About 60% of the γH2AX foci remained 48 hrs after the end of treatment in SN-38→RHPS4 combination, while the opposite sequence allowed to reduce the number of DNA damage foci to 10% (Figure 4B). Analysis of telomeric DNA damage by measure the percentage of cells showing more than four colocalization between γH2AX and the telomeric marker TRF1 (TIF-positive cells) as well as the average number of TIF, revealed that SN-38 induced telomere damage in almost the totality of damaged cells that was stabilized in the SN-38→RHPS4 combination (Figure 4C-E).

Our results clearly demonstrate that the DNA damages elicited by G4 ligands cannot be efficiently repair in camptothecin-treated cells.

Novel camptothecins and RHPS4 combination limits the growth of colon cancer cells both in vitro and in xenografts: use of γH2AX as marker of tumor response
We finally evaluated the interaction between the G4 ligand RHPS4 and three novel camptothecins with a more favorable therapeutic and pharmacological profile than clinically used camptothecins, including IDN5174, ST1968 and ST1481. As reported in Figure 5A, the treatment with camptothecins followed by RHPS4 was highly effective as revealed by the reduction of survival of HT29 cells by one to three order of magnitude, depending on the camptothecin used. Again, this effect was markedly dependent on the sequence employed, since the opposite sequence of treatment produced only a slight reduction of clonogenic ability. The results have been confirmed in another colon carcinoma line (Figure 5B) and the analysis of these data by using the CI confirmed that the optimal sequence has a strong synergistic effect on cell survival (Figure 5C-D).

Based on in vitro results, experiments were performed in vivo on HT29 tumor-bearing mice. In particular, we focused our attention to the combination of RHPS4 with ST1481, an orally bioavailable camptothecin currently undergoing clinical trials. ST1481 confirmed its relevant antitumor efficacy, being tumor weight significantly reduced ($P < 0.001$) compared to untreated and to mice treated with RHPS4 alone (Figure 6A and Supplemental Table I). The combination with RHPS4 produced an improved therapeutic efficacy as it is evident by the tumor growth delay of 33 days, significantly increased compared to ST1481 (24 days, $P = 0.004$) and to RHPS4 (6 days, $P < 0.001$) alone, and by the complete tumor regression in half of the treated mice (Figure 6A and Supplemental Table I). This inhibitory effect on tumor growth of combination treatment led to a marked increase in the survival of mice significantly higher ($P < 0.001$) compared to any single treatment groups (Figure 6B and Supplemental Table I). Of note, a further improved antitumor efficacy has been observed when a second cycle of treatment was administered. Mice receiving two cycles of treatment had a significant advantage ($P < 0.001$) in terms of reduction of tumor mass and this effect persisted for almost 2 months (55 days in T-C and nearly 100% complete response rate in 7 out of 8 mice). This marked and prolonged antitumor effect produced an
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impressive increase in overall mice survival of 269% that was significantly different ($P< 0.001$) to all other treatment groups (Figure 6B and Supplemental Table I).

To verify if activation of damage response can be used as surrogate marker of tumor response, immunohistochemical analysis of $\gamma$H2AX was performed in tumor specimens. ST1481 markedly increased the $\gamma$H2AX staining, the number of positive nuclei/mm$^2$ increased of about 8-fold compared to untreated. The number of $\gamma$H2AX-positive cells was significantly ($p= 0.003$) reduced up to 50% one week after the end of ST1481 treatment, while it was still high when ST1481 was followed by RHPS4 administration.

Our results demonstrate the high therapeutic efficacy of ST1481/RHPS4 combination suggesting that persistent activation of DNA damage response is a key determinant of the antitumor effect.
Discussion

Stabilization of telomeric G4 can be considered an original strategy for controlling tumor growth, making G4 ligands attractive potential anticancer agents (38). We recently showed that one of them, the RHPS4 molecule, has an antitumor effect, by selectively inducing telomere damage in xenografted tumor models. More recently, we have uncovered a specific link between RHPS4 and chemosensitivity toward camptothecins in colorectal tumors. In the present study we have investigated the mechanism(s) involved in this specific drug interaction.

We confirmed the strong synergistic interaction between camptothecin and RHPS4 by using other G4 ligands and novel camptothecin analogues, clearly demonstrating that the synergistic effect between Topo I inhibitors and telomere-targeting agents is a general phenomenon. These results have been obtained by using cytotoxic doses of camptothecins, able to reduce cell viability and induce DNA damage, and therefore they are reasonably ascribed to topoisomerase I-mediated effects.

Strikingly, the best synergistic drug interaction is observed if camptothecins are given before G4 ligands. Thus, camptothecin-treated cells are either more prone to be damaged by RHPS4 or less efficient to repair RHPS4-dependent damages or both. In favor of the second possibility, we did not observe an increased rate of damage due to RHPS4 in camptothecin-treated cells as compared to controls but rather a persistence of the damage. This suggests that Topo I is normally required to repair the telomeric damages elicited by G4-ligands and that its inactivation by camptothecin prevents or impairs this repair. In agreement with this hypothesis, we found that Topo I is enriched at telomeres of RHPS4-treated cells. This unveils a function of Topo I at telomeres in relation with G4 formation. These results, together with in vitro results showing that Topo I binds to G4 tetraplexes (39) and functionally interacts with the Werner helicase (40) that unwinds these DNA structures (41), suggest that in vivo Topo I resolves the G4 tetraplexes that either
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occur during the transcription, replication or recombination of telomeric DNA or are the outcome of G4 stabilizing agents. Whether this function of Topo I involves its DNA relaxation activity or other of its functions (42) remains to be further explore.

These results suggest a key role of Topo I on telomere-based therapy and demonstrate that combination of SN-38 with G4 ligands make cells unable to recover from drug-induced cytotoxicity. Impressively, mice treated with ST1481/RHPS4 combination showed an inhibition and delay of tumor growth and an increased survival. This is particularly relevant from a clinical point of view, since ST1481 has completed phase II clinical trial in advanced ovarian cancers showing activity and a manageable safety profile (29). Analysis of damage response in vivo by measuring the $\gamma$H2AX-positive cells in the tumor samples upon the different treatments, revealed that while the number of $\gamma$H2AX-positive cells was reduced four days after the end of ST1481 treatment, it was still high when ST1481 was followed by RHPS4 administration.

In conclusion, our studies provide a compelling argument to suggest that the integration of G4 ligands to camptothecin-based treatment might be a highly valuable therapeutic combination. Assaying for the persistence of DNA damage response in tumor might be used as a surrogate marker of tumor response.
References


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Figure Legends

Figure 1. Inhibition of Topo I, but not of Topo IIα has a strong synergistic interaction with G4 ligands. HT29 cells were treated with SN-38 or ADR for 2 hrs or with RHPS4, CORON and PIP-PIPER (1,7) for 96 hrs. In the combination experiments, two different sequence of drug administration were evaluated. Percentage of cell survival of SN-38 (A) and ADR (C) alone and in combination with G4 ligands. Surviving fractions were calculated as the ratio of absolute survival of the treated sample/absolute survival of the control sample. Combination index (CI) for SN-38 (B) or ADR (D) was calculated by the Chou-Talalay method. Data plotted are CI at 50% (white squares), 75% (light gray squares), 90% (dark gray squares), and 95% (black squares) fraction killed. Data represents the means ± SD of three independent experiments.

Figure 2. Cells exposed to the SN-38→RHPS4 combination showed a strong perturbation of cell cycle and cell death. HT29 cells were treated with 0.5 μM SN-38 for 2 hrs or 0.5 μM RHPS4 for 48 hrs. In the combination experiment, the medium containing the first drug was removed and replaced with fresh medium in presence or absence of the second drug. (A) Cell cycle analysis after PI staining was performed by flow cytometry at 12 and 48 hrs after the end of SN-38 treatment. The percentages of cells in the different phases of cell cycle were reported inside the relative histogram. A representative out of three independent experiments is shown. (B) Percentage of cell death in untreated (black bar), and cells exposed to the following treatment: RHPS4 (white bar), SN-38 (gray bar), SN-38 followed by RHPS4 (hatched bar) and RHPS4 followed SN-38 (dotted bar). The mean of four independent experiments with comparable results is shown. Error bars indicate ± SD. P value is ** p< 0.01. Analysis was performed at 48 hrs after the end of SN-
Inhibition of Topo I stabilizes telomere damage 38 treatment. (C) Representative images of the cells exposed to the indicated treatments stained with Hoechst. Arrows indicate the presence of apoptotic bodies.

**Figure 3. Topo I, but not Topo IIα, is stabilized at the telomeric regions upon treatment with G4 ligands.** (A) ChIP experiments on BJ-HELT fibroblasts untreated and treated for 24 hrs with 0.5 μM RHPS4, 0.05 μM CORON and 4 μM PIP-PIPER (1,7), or for 2 hrs with 0.5 μM SN-38 (B). Protein extracts from cells were subjected to ChIP assay using the indicated antibodies. The total DNA (input) represents 10 and 1% of genomic DNA. Southern blot analysis was performed by using telomeric (Telo) or ALU repeat-specific probes. (C) and (D) The signals obtained were quantified by densitometry, and the percentage of precipitated DNA was calculated as a ratio of input signals and plotted. Four independent experiments were evaluated and error bars indicate the standard deviation (SD).

**Figure 4. Stabilization of DNA damage in SN-38→RHPS4 combination.** BJ-EHLT fibroblasts were treated with 0.5 μM SN-38 for 2 hours or 0.5 μ RHPS4 for 48 hrs. In the combination experiments, the medium containing the first drug was removed and replaced with fresh medium in presence or absence of the second drug. Cells were processed for IF using antibodies against γH2AX and TRF1 to mark telomeres. Percentage of γH2AX- (A) and TIF-positive cells (C) in untreated (-) and cells exposed to the indicated treatments. Cells with four or more γH2AX/TRF1 foci were scored as TIF positive. Analysis was performed from 12 to 48 hrs after the end of treatments. Average number of γH2AX (B) and γH2AX/TRF1 (D) foci in the indicated samples. The mean of four independent experiments with comparable results is shown. Error bars indicate ± SD. P values are *p <
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0.05 and ** p< 0.01. (E) Representative images of IF in the indicated samples acquired with a Leica Deconvolution microscope (magnification 100x) are reported.

Figure 5. Cytotoxic activity of novel camptothecins in combination with RHPS4. HT29 and HCT116 coloncarcinoma cells were treated with ST1481, IDN5174 or ST1968 alone or in combination with RHPS4. Two different sequence of drug administration were evaluated. Percentage of cell survival of the HT29 (A) and HCT116 cells (B) upon the different treatments. Surviving fractions were calculated as the ratio of absolute survival of the treated sample/absolute survival of the control sample. Combination index (CI) calculated by the Chou-Talalay method in HT29 (C) and HCT116 cells (D) upon the different treatments. Data plotted are CI at 50% (white squares), 75% (light gray squares), 90% (dark gray squares), and 95% (black squares) fraction killed. Data are means ± SD of three independent experiments.

Figure 6. Antitumor effect of ST1481 and RHPS4 on tumor bearing-mice. HT29 tumor-bearing mice were treated with RHPS4 or ST1481 alone or in combination as follows: ♦, saline solution; □, RHPS4 d 7-21.; △, ST1481 days 7, 11, 15, 19; ○, ST1481 days 7, 11, 15, 19 and RHPS4 on days 8-10, 12-14, 16-18 and 20-25; ▲, ST1481 days 7, 11, 15, 19 followed by a second cycle of treatment at days 30, 34, 38 and 42; ⬤, ST1481 days 7, 11, 15, 19 and RHPS4 on days 8-10, 12-14, 16-18 and 20-25. A second cycle of treatment was administered by giving ST1481 on days 30, 34, 38, 42 and RHPS4 on days 31-33, 35-37, 39-41, 43-48. (A) Mean ± SD tumor weight (mg) and (B) survival curves are reported. Arrows indicate start of first and second cycle of treatment. Immunohistochemical analysis of γH2AX in tumor sections from untreated mice or mice treated with ST1481 given alone or in combination with RHPS4: a, saline solution; b,
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ST1481 (1 day after the end of treatment); c, ST1481 (7 days after the end of treatment); d, ST1481 followed by RHPS4. (C) Representative images of γH2AX staining. Magnification, x20. Representatives out of three independent experiments with comparable results are shown. (D) Number of γH2AX-positive nuclei/mm² in the indicated samples. Error bars indicate ± SD. P value is *p < 0.01.
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Footnotes

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For reprint requests: Dr. A. Biroccio, or Dr. C. Leonetti, Experimental Chemotherapy Lab. Regina Elena Cancer Institute, Via delle Messi d’Oro n. 156, 00158 Roma, Italy.
Figure 2

(Birocchio et al.)

A

N. of cells

T=12 hrs

Untreated

SN-38

G1/G0=41.8%
S=51.3%
G2/M=6.9%

G1/G0=27.1%
S=49.8%
G2/M=12.8%

T=48 hrs

DNA content

RHP54

SN-38

RHP54

RHP54

SN-38

SN-38

RHP54

G1/G0=51.4%
S=49.3%
G2/M=5.2%

G1/G0=67.7%
S=27.1%
G2/M=5.2%

G1/G0=58.7%
S=35.4%
G2/M=6.1%

G1/G0=55.9%
S=35.4%
G2/M=8.6%

G1/G0=70.7%
S=28.8%
G2/M=8.5%

G1/G0=55.3%
S=32.4%
G2/M=12.3%

B

% of cell death

**

Untreated

RHP54

SN-38

SN-38

RHP54

C

Untreated

RHP54

SN-38

SN-38

RHP54

Hoechst 33258

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DNA damage persistence as determinant of tumor sensitivity to the combination of Topo I inhibitors and telomere-targeting agents

Annamaria Biroccio, Manuela Porru, Angela Rizzo, et al.

Clin Cancer Res  Published OnlineFirst February 25, 2011.

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