Therapeutic Potential of Nitric Oxide-Modified Drugs in Colon Cancer Cells

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ABSTRACT

We have examined the influence of the nitric oxide (NO)-modified anti-inflammatory drug ([S,R]-3-phenyl-4,5-dihydro-5-isoxasole acetic acid (VGX-1027) named GIT-27NO or the NO-modified antiviral drug saquinavir (Saq) named Saq-NO on two colon cancer cell lines, mouse CT26CL25 and human HCT116. The effects of the drugs on cell viability, apoptosis, proliferation, and metastatic potential were analyzed. The release of NO and oxygen and nitrogen species was also determined. The efficacy of the drugs was evaluated in vivo in BALB/c mice injected with CT26CL25 and human HCT116. The effects of the drugs on cell viability, apoptosis, proliferation, and metastatic potential were analyzed. The release of NO and oxygen and nitrogen species was also determined. The efficacy of the drugs was evaluated in vivo in BALB/c mice injected with CT26CL25 and human HCT116. Both agents suppressed the growth of colon cancer cells in vitro and reduced tumor volume in syngeneic BALB/c mice. However, their mechanisms of action were different because GIT-27NO released larger amounts of nitrite than Saq-NO in cell cultures and its antitumor action depended on the intracellular NO release inside the cells. On the contrary, Saq-NO released barely detectable amounts of NO and its antitumor action was NO-independent. In fact, cotreatment with an NO-peroxynitrite scavenger revealed that GIT-27NO but not Saq-NO acts through peroxynitrite-mediated cell destruction. At the cellular level, GIT-27NO prevalently induced proapoptotic signals followed by caspase-dependent apoptosis. In contrast, Saq-NO blocked cell proliferation, changed the adhesive, migratory, and invasive properties of the cells, and decreased metastatic potential in vivo. In conclusion, differences in NO release and oxidative stress generation between GIT-27NO and Saq-NO resulted in different mechanisms that caused cell death.

Introduction

Colorectal cancer remains the second most frequent cause of cancer-related death despite recent major prophylactic and therapeutic advancements that have reduced its mortality rate by 9% (Wolpin and Mayer, 2008; Giuliani et al., 2010; Labianca and Merelli, 2010). This severity of colorectal cancer is probably due to development of metastasis and chemoresistance of colorectal cancer cells (Gallagher and Kemeny, 2010; Zhang et al., 2012). Recent data revealed promising potential for drugs initially designed for treatment of inflammation and infection in therapy of cancers whose tumorigenesis is related to the above-mentioned processes.

It is known that nonsteroidal anti-inflammatory drugs (NSAIDs) reduce the incidence of colon cancer in clinical trials (Coimbra et al., 2009; Rothwell et al., 2010, 2011) and that attachment of a NO moiety to the parent NSAIDs reduced gastrotoxicity and increased their antitumor properties owing to an intrinsic feature of this reactive molecule to induce tumor cell death (Yeh et al., 2004; Gao et al., 2005; Rigas and Williams, 2008).

ABBREVIATIONS: NSAID, nonsteroidal anti-inflammatory drug; NO, nitric oxide; VGX-1027, ([S,R]-3-phenyl-4,5-dihydro-5-isoxasole acetic acid; ROS, reactive oxygen species; RNS, reactive nitrogen species; Saq, saquinavir; DETA NONOate, diethylenetriamine NONOate; MEG sulfate, (2-mercaptoethyl)-guanidine sulfate; SNAP, S-nitroso-N-acetyl-D,L-penicillamine; SIN-1 chloride, linsidomine; AnnV, annexin V-FITC; DHR, dihydrorhodamine 123; PI, propidium iodide; p, phospho; PI3K, phosphatidylinositol 3-kinase.
(S,R)-3-Phenyl-4,5-dihydro-5-isoxasole acetic acid (VGX-1027) is an anti-inflammatory compound in early clinical development for the treatment of rheumatoid arthritis and type 1 diabetes. VGX-1027 has elicited immunomodulatory and anti-inflammatory effects mediated by down-regulation of interleukin-1β, tumor necrosis factor, nuclear factor-κB, and inducible nitric-oxide synthase expression (Stojanovic et al., 2007; Stosic-Grubacic et al., 2007). VGX-1027 does not possess antitumor properties. Covalent linkage of a NO moiety to VGX-1027 generated a novel drug, GIT-27NO, effective against numerous tumor cell lines (Maksimovic-Ivanic et al., 2008; Mijatovic et al., 2008, 2010; Donia et al., 2009). GIT-27NO liberates NO upon encountering the cell or cell-secreted products. Internalized NO leads to higher production of reactive oxygen species (ROS) and reactive nitrogen species (RNS) influencing the activity of essential signaling pathways, transcription factors, and pro- and antiapoptotic molecule expression and, as a consequence, elicited caspase-dependent or -independent apoptosis (cell death by autophagy) (Maksimovic-Ivanic et al., 2008; Mijatovic et al., 2008, 2010; Donia et al., 2009).

An important structural and pharmacological difference with GIT-27NO from other NO-NSAIDs such as NO-aspirin whose antitumor properties depend on the original substance is that the NO carrier and NO itself are in direct linkage of the NO moiety to original VGX-1027 (Kashfi and Rigas, 2007). This is important because genotoxicity was observed with the linker used to generate NO-aspirin, which resulted in cessation of the clinical trials with this agent (NicOx press release, 2007, http://www.nicox.com/files/pdf/PR2007061800EN.pdf).

The antitumor properties of protease inhibitors designed for treatment of human immunodeficiency virus infection are well documented (Sgadari et al., 2003; Bernstein and Dennis, 2008; Chow et al., 2009). The prototypical protease inhibitor saquinavir (Saq) significantly lowered the incidence of human immunodeficiency virus-related cancers (Lebbé et al., 1998; Bower et al., 1999; Niehues et al., 1999; Sgadari et al., 2003). However, numerous side effects hamper the use of Saq and other protease inhibitors as antineoplastic drugs. A NO derivative of Saq was developed with the aim of improving its anticancer efficacy (Maksimovic-Ivanic et al., 2009). Compared with the parent drug Saq, Saq-NO exhibits lower in vitro and in vivo toxicity and increased anticancer action. In addition, the antiretroviral activity of Saq-NO was similar to that of the parent compound (Maksimovic-Ivanic et al., 2009; Canducci et al., 2011; Donia et al., 2011; Mijatovic et al., 2011). Although Saq-NO primarily exerted its anticancer action via inhibition of cell proliferation, apoptosis was also induced in some circumstances (Donia et al., 2011; Mijatovic et al., 2011). Moreover, Saq-NO efficiently sensitized tumor cells to tumor necrosis factor-related apoptosis-inducing ligand and chemotherapy, regardless of p53, P-glycoprotein, multidrug resistance-associated protein 1, or breast cancer resistance protein 1 expression (Rothweiler et al., 2010; Donia et al., 2011; Mijatovic et al., 2011). Unlike the parent compound Saq, Saq-NO transiently up-regulated Akt (Maksimovic-Ivanic et al., 2009; Mijatovic et al., 2011). Inhibition of Akt has been related to the toxic effects of Saq (Schütt et al., 2004; Gupta et al., 2005). Because Saq-NO releases minor amounts of NO, it is unlikely that its lower toxicity and enhanced antitumor action are immediate consequences of NO release (Maksimovic-Ivanic et al., 2009).

In this study, we compared the responsiveness of two metastatic colon cancer cell lines with those of GIT-27NO and Saq-NO. Both compounds strongly inhibited the growth of colon cancers in vitro and in vivo. Whereas GIT-27NO acted through NO-mediated caspase-dependent apoptosis, without affecting metastatic potential, Saq-NO converted cells into a nonproliferative phenotype and abrogated their metastatic potential.

Materials and Methods

Reagents and Cells. Saq-NO (OX1001) and GIT-27NO (OX27-NO) were obtained from OncoNox (Copenhagen, Denmark). DETA NONOate, MEG sulfate, SNAP, and SIN-1 chloride were from Cayman Chemical (Ann Arbor, MI). Doxorubicin was from Sigma-Aldrich (Milan, Italy). For flow cytometry studies, annexin V (AnnV)-FITC was obtained from BD Pharmingen (San Diego, CA), and acridine orange was from Labo-Moderna (Paris, France). Moloney leukemia virus reverse transcriptase and random primers used for reverse transcription were from Fermentas (Vilnius, Lithuania). Real-time polymerase chain reaction (PCR) was performed with SYBR Green PCR Master Mix from Applied Biosystems (Carlsbad, CA). The pan-caspase inhibitor N-benzoyloxycarbonyl-Val-Ala-Asp was purchased from R&D Systems (Minneapolis, MN). Other reagents were purchased from Sigma-Aldrich (St. Louis, MO) unless stated otherwise.

Murine (CT26CL25) and human (HCT116) colon cancer cell lines were obtained from American Type Culture Collection (Manassas, VA). Cells were routinely maintained in HEPES-buffered RPMI 1640 medium supplemented with 10% fetal calf serum, 2 mM L-glutamine, 0.01% sodium pyruvate, 5 × 10−5 M 2-mercaptoethanol, and antibiotics (culture medium) at 37°C in a humidified atmosphere with 5% CO2. Cells were collected with 0.25% trypsin-1 mM EDTA solution in PBS and seeded at a density of 104/well in 96-well plates or 2 × 105/well in six-well plates, unless otherwise indicated.

Animals. Six- to 8-week-old male BALB/c mice, weighing 25 to 28 g, were purchased from Harlan-Nossan (San Pietro al Natisone, Udine, Italy). The mice were kept under standard laboratory conditions (non-specific pathogen-free) with free access to food and water. The animal studies were performed in accordance with local guidelines and approved by the institutional animal care and use committee (Fugone et al, 2012).

Cell Viability Evaluation. Cells were seeded in 96-well plates, incubated for 24 h in the presence of different concentrations of GIT-27NO, Saq-NO, VGX-1027, or conventional NO donors such as DETA NONOate, sodium nitroprusside (SNP), SIN-1 chloride, SNAP, or the peroxynitrite scavenger MEG sulfate, and viability was estimated using crystal violet (CV) staining for adherent cells as described previously (Flick and Gifford, 1984). The viability of treated cells is shown as a percentage of value obtained for untreated cultures that was arbitrarily set to 100%. For evaluation of cell viability after the treatment in a three-dimensional environment, cells (5 × 105/well) were plated onto 96-well plates that were coated with a thin layer of Matrigel (10 mg/ml; BD Biosciences Discovery Labware, Bedford, MA) (Kleinerman et al., 1982). Cultures were incubated for 72 h with 100 μg doses of Saq ± NO and photographed by using a phase microscope.

Detection of Extracellular NO Release, Intracellular NO Accumulation, and ROS Production. After the cell culture treatment with GIT-27NO, Saq ± NO, DETA NONOate, SNP, SIN-1 chloride, or SNAP, extracellular nitrite accumulation was detected by the Griess reaction as described previously (Maksimovic-Ivanic et al., 2008). Intracellular NO accumulation was evaluated by the fluorescent dye DAF-FM diacetate (Invitrogen, Carlsbad, CA). ROS production was detected with redox-sensitive dihydrorhodamine 123 (DHR). Fluorescence intensity of DAF- and DHR-stained cultures were analyzed by a Chameleon multiplate reader (Hidex, Turku.
Flow Cytometry. After treatment of the cell cultures seeded in six-well plates with GIT-27NO, Saq-NO, VXG-1027, or Saq, cell cycle analysis, early apoptosis detection with annexin V-PI, caspase activation with ApoStat, and cell proliferation of carboxyfluorescein diacetate succinimidyl ester-stained cells were performed as described previously (Maksimovic-Ivanic et al., 2008, 2009). Cells were analyzed by a FACSCalibur flow cytometer with CellQuest Pro software.

Immunocytochemical Detection. The expression of p53 was assessed immunocytochemically as described previously (Maksimovic-Ivanic et al., 2009). The cells were cultivated on glass chamber slides (3 × 10^5 cells/well), and p53 expression was analyzed with specific antibodies against p53 (1:500; Santa Cruz Biotechnology, Inc., Santa Cruz, CA). Detection was performed with the rabbit ExtrAvidin Peroxidase staining kit according to the manufacturer's instructions (Sigma-Aldrich), using diaminobenzidine (DAB System) as a substrate. The cells were counterstained with Mayer's hematoxylin, and slides were mounted with Glycer-gel mounting medium (Dako Denmark A/S, Glostrup, Denmark).

Induction of Colon Cancer and Experimental Treatments. CT26CL25 cells (5 × 10^5) were injected subcutaneously into the flank of each mouse using a 0.6-mm needle. Tumor growth was observed twice a week and measured with a caliper (two perpendicular diameters), and the tumor volume (mm^3) was calculated according to the formula: \[ V = \frac{1}{2} \times a \times b^2 \], where \( a \) is the longest and \( b \) is the shortest diameter. When the tumors were palpable, approximately 12 days after induction, the animals were randomly allocated to five groups of 10 and were treated daily, respectively, with Saq, Saq-NO (10 mg/kg), vehicle (dimethyl sulfoxide 20%) for 15 consecutive days and doxorubicin (2 mg/kg) for 5 consecutive days as a positive control. In a different set of experiments, after tumor induction, animals were randomly allocated to four groups of 10 mice treated, respectively, with GIT-27NO (0.5 mg/mouse), doxorubicin, or vehicle. One group of mice was left untreated. Postrandomization analysis revealed no significant differences in tumor volumes at the beginning of the treatment among the different groups.

Induction of Lung Metastasis. For evaluation of the impact of Saq and Saq-NO on metastatic potential, CT26CL25 cells were treated with 37.5 μM GIT-NO for 6 h when total RNA was isolated with TRI Reagent Solution (Ambion, Austin, TX) according to the manufacturer's instructions. Reverse transcription and PCR amplification were performed as described previously (Donia et al., 2011). Primer pairs were the following: Bax, 5'-TGAAGACAGGGGCTTTTTTTT-3' and 5'-AATTCGCCCCAGAGACCTCG-3'; Bcl-2, 5'-TCCGAGATGTGCGACTGAG-3' and 5'-CCCTAAGGTCTTCCACACA-3'; Bcl-xL, 5'-CCGGAGGCTTCTGATGATC-3' and 5'-TGGAATCGGACTCTGCAATA-3'; caspase 3, 5'-TCTGACAGTGGAAAATCCCAA-3'; caspase 8, 5'-CTCACTTCCATGCAAC-3' and 5'-CTCTACGTTCACCAGC-3'; β-actin, 5'-CCGGAGAGCTTCTGATGATC-3' and 5'-TGGGAATCGGACTCTGCAATA-3'; and 5'-AATTCGCCCCAGAGACCTCG-3'; and 5'-TCCGAGATGTGCGACTGAG-3'. The expression level of each gene was calculated using formula 2^-ΔΔCT, where Ct is the cycle threshold value of the gene of interest and Cta was the cycle threshold value of β-actin. Expression levels are presented as fold increase of values obtained from untreated cultures that were arbitrarily set to 1.

Results

NO-Modified Drugs Inhibited the Growth of Colon Cancer Cells In Vitro and In Vivo. To evaluate the impact of NO modification on activity of the parent drugs, human HCT116 and mouse colon CT26CL25 cell lines were exposed
to different concentration of drugs for 24 h, and cell viability was estimated with the CV test. As shown previously, treatment with the parent drug VGX-1027 did not affect the viability of either cell line (Fig. 1A, left). NO attachment to the parent compound created a potent anticancer agent. The viability of both human and mouse cell lines was significantly diminished upon the GIT-27NO treatment with IC_{50} values of approximately 75 μM (Fig. 1A, left). On the other hand, both original and NO-modified Saq reduced cell growth, but the IC_{50} dose for Saq-NO was significantly lower than the IC_{50} dose for Saq (18.8 versus 90.5 μM for HCT116 and 37.5 versus 111.3 μM for CT26CL25 cells) (Fig. 1A, right). It is evident that NO modification significantly improved the in vitro anticancer potential of the parent drugs.

We next investigated their potential in vivo using a syngeneic tumor model in BALB/c mice. Saq-NO was administered daily starting on day 14 after tumor inoculation. The tumor volumes were significantly inhibited (p < 0.05) from day 16 until day 23 of the study in the groups treated with Saq-NO compared with those in vehicle-treated mice (Fig. 1B). The potency of Saq-NO was similar to that observed with the positive control chemotherapeutic drug doxorubicin. In addition,

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**Fig. 1.** NO-modified drugs decreased tumor cell growth. A, HCT116 and CT26CL25 cells (10^4 cells/well) were treated with a range of concentrations of the indicated drugs for 24 h, and then cell viability was determined by CV assay. The data are presented as the mean ± S.D. from a representative of three independent experiments. *, p < 0.05, refers to untreated cultures. B, tumors were induced by subcutaneous implantation of 5 \times 10^6 CT26CL25 cells. Then after 14 days to allow the tumors to take in the mice, the mice were injected intraperitoneally with the drug daily for 14 days. Tumor volumes were measured two times per week until the end of the experiment.
the treatment with Saq also induced a significant reduction in the tumor volume (Fig. 1B).

The administration of GIT-27NO significantly reduced the growth of the murine colon cancer cell line CT26CL25 in BALB/c mice from day 23 until the end of the study (Fig. 1B). The positive control doxorubicin reduced tumor growth significantly from day 19 to day 27 after injection of colon cancer cells.

**GIT-27NO, but Not Saq-NO, Induced Caspase-Dependent Apoptosis.** To evaluate the cause of decreased tumor cell viability, CT26CL25 and HCT116 cells were treated with IC<sub>50</sub> doses of NO-modified compounds and the same doses of corresponding original drugs, and cell cycle analysis was performed. Application of Saq did not affect cell cycle distribution significantly compared with that in the control (Fig. 2A, left). Treatment with Saq-NO for 24 h led to cell cycle arrest in the G<sub>0</sub>/G<sub>1</sub> phase of the cell cycle without considerable accumulation of hypodiploid cells or a decreased percentage of cells in the S phase (Fig. 2A, left). In agreement with these results AnnV-PI double staining revealed the absence of early and late apoptosis (not shown). On the other hand, treatment of CT26CL25 cells with GIT-27NO for 24 h increased the percentage of cells in the sub-G compartment (Fig. 2A, right). Exposure of HCT116 cells to GIT-27NO also elevated the amount of apoptotic cells, but the effects were not as great as those observed with CT26CL25 cells (Fig. 2A, right). Increased percentages of both AnnV<sup>+</sup>PI<sup>+</sup> and double positive (AnnV<sup>+</sup>PI<sup>+</sup>) CT26CL25 and HCT116 cells were detected after 24 and 48 h, respectively (Fig. 2B). Staining of CT26CL25 cells with ApoStat revealed significant activation of caspases after the treatment with an IC<sub>50</sub> dose of GIT-27NO (Fig. 2C). In concordance with this result, enhanced gene expression of caspase 8 and of the effector caspase 3 was observed (Fig. 2D). Cotreatment of CT26CL25 cells with the

![Fig. 2. GIT-27NO-induced caspase-dependent apoptosis. Cells were treated with an IC<sub>50</sub> dose of the drugs and cell cycle analysis (A) and staining by AnnV-PI (B) and ApoStat (C) was performed by flow cytometry after 24 or 48 h for CT26CL25 and HCT116 cells, respectively. (SSCH, side scatter height). D, real-time PCR analyses for caspase 3 and caspase 8 were performed after 6 h of incubation in the presence of the drug, and data are presented as relative expression of mRNA. E, mitochondrial membrane depolarization of JC-1-stained CT26CL25 cells was determined by flow cytometry after 24 h. F, real-time PCR analyses for Bax, Bcl-2, and Bcl-X<sub>l</sub> were performed as mentioned above. G, the presence of p53 in CT26CL25 cells after incubation for 24 h without (control) or with GIT-27NO was detected by immunocytochemical analysis and analyzed by light microscopy.](image-url)
pan-caspase inhibitor Z-VD (20 μM) and an IC_{50} dose of GIT-27NO for 24 h partly reversed cell viability (47.4 ± 0.9% in GIT-27NO-treated cultures versus 69.5 ± 3.4% in co-treated cultures), thus confirming the contribution of caspase activation in tumouricidal action of the drug. Mitochondrial membrane depolarization determined by the fluorescent dye JC-1 indicated involvement of the mitochondrial pathway in apoptosis triggered by GIT-27NO in CT26CL25 cells but not in Bax-deficient HCT116 cells (Fig. 2E) (Van Geelen et al., 2004). This effect was accompanied by dominant expression of Bax in both cell lines. Because enhanced expression of cytoprotective Bcl family members Bcl-2 and Bcl-XL (Fig. 2F) was detected but was significantly less pronounced than expression of the proapoptotic Bax protein in the mouse colon line, the balance between pro- and antiapoptotic mediators was shifted toward the proapoptotic signal (Bax/Bcl-2 = 3.1; Bax/Bcl-XL = 24.9). Finally, remarkably elevated total p53 in cells exposed to GIT27-NO (Fig. 2G) is well synchronized with the dominant proapoptotic signal. In summary, GIT-27NO induced caspase-dependent apoptosis in both colon cancer cell lines, whereas the anticancer action of Saq-NO was not caused by the apoptotic process but rather resulted from inhibition of proliferation.

**Saq-NO Suppressed Proliferation of Colon Cancer Cells.** The lack of apoptosis and cell cycle arrest observed in both cell lines upon treatment with Saq-NO indicated that inhibition of proliferation could result in decreased viability. To prove this, the cells were stained with carboxyfluorescein diacetate succinimidyl ester and then treated with an IC_{50} dose of Saq-NO or the same dose of original drug, and flow cytometric analysis was performed after 72 h. Whereas treatment of CT26CL25 cells with Saq exerted no effect on cellular proliferation, Saq-NO almost completely blocked the division of cells (11.9% of divided cells versus 86.6 and 90.1% in control and Saq-treated cells, respectively). Inhibition of HCT116 cell proliferation was less pronounced (50% of divided cells versus 90% and 70% in control and Saq-treated cells, respectively. We next examined whether this effect of Saq-NO required the continuous presence of the drug. For that purpose, CT26CL25 cells were pretreated with Saq-NO for 24 h, and then the drug was removed and cell viability was measured after an additional 24, 48, or 72 h of incubation (Fig. 3A). Exposure of CT26CL25 cells to Saq-NO irreversibly blocked the proliferative ability of the cells. To clarify the molecular background of this effect, the PI3K/Akt signaling pathway as a pivotal regulator of cell proliferation was examined. Whereas p-Akt levels were transiently up-regulated upon the treatment with NO-modified Saq, in contrast to that with the original drug, the downstream target of mTOR, S6 kinase, was continuously inactivated through the decreased rate of phosphorylation on Ser240/244 (Fig. 3B). This phenomenon showed a similar pattern in both cell lines tested and is compatible with the previously observed decrease in cell dividing potential. Decreased expression of cyclin D3 revealed by Western blot in CT25CL26 cells indirectly confirmed the abolished activity of the downstream part of the PI3K/Akt pathway (Fig. 3C). In addition, Saq-NO remarkably elevated p53 protein expression without preventing its degradation as judged by the level of p53 phosphorylated on Ser20 (Fig. 3C). In contrast to the modified drug, Saq strongly induced phosphorylation of p53, which protected this molecule from murine double minute (mdm2) mediated degradation whereas total p53 expression was not significantly affected (Fig. 3C) (Mijatovic et al., 2010).

**Saq-NO Significantly Reduced Metastatic Properties of Colon Cancer Cells In Vitro and In Vivo.** To evaluate the antimetastatic potential of original and NO-modified Saq, we examined the growth of cells on reconstituted basement membrane (Matrigel) during 3 days in the presence of subtoxic doses of the drugs. CT26CL25 and HCT116 cells elicited different patterns of growth on Matrigel. Whereas HCT116 cells showed rounded morphology and formed small clusters (Fig. 4A, left), CT26CL25 cells made net-like structures and displayed elongated morphology (Fig. 4A, right). Independently of the morphologies of the colonies, Saq-NO treatment during 72 h strongly inhibited Matrigel growth in both types of colon cancer cells, whereas the inhibitory potential of the novel modified drug was greater than that of the unmodified Saq (Fig. 4A). In a similar manner Saq-NO was found to be superior in decreasing migration, invasion, and adhesive properties of cells compared with its parent compound (Fig. 4B). To confirm the permanent reduction of metastatic properties, the cells were pretreated with drugs, and formation of lung metastases was examined. At day 18, one animal in the control group died, and 2 animals displayed massive lung metastases (>120 nodules per mouse, diameter ~3 mm each). Pretreatment of the cells with Saq resulted in a lower presence of metastases (n1 = 120 nodules, diameter ~3 mm; n2 = 90 nodules; and n3 = 30 nodules, diameter ~2 mm), but its efficacy was significantly less than that of Saq-NO. In the group of animals receiving Saq-NO-pretreated cells only, one animal exhibited mild metastases (n = 59, diameter ~1 mm). Taken together, these results show that Saq-NO exerted its tumoricidal activity against colon cancer cells through inhibition of proliferation and a decrease in metastatic potential.

**Role of NO in the Antitumor Effects of NO-Modified Compounds.** We next compared the release of NO into the culture medium of CT26CL25 cells in the presence of the NO-modified drugs or NO donors such as SNAP, SIN-1, SNP, and DETA NONOate. Although both GIT-27NO and Saq-NO released lower amounts of NO than the NO donors, they exhibited more powerful reduction of cell viability than the latter (Fig. 5, A and B). Even if GIT-27NO formed higher amounts of nitrites than Saq-NO, the diminished number of viable cells in cultures did not correlate with accumulated nitrites. Only GIT-27NO efficiently induced NO release inside the cells (Fig. 5C). On the other hand, both NO-modified compounds induced production of ROS (Fig. 5D). More sensitive measurement of NO release performed by flow cytometric analysis confirmed the previous results (Fig. 5, E and F). Concomitant treatment with hemoglobin, an extracellular scavenger of NO, resulted in restored viability of cells exposed to GIT-27NO, confirming the contribution of released NO to the tumoricidal action of the drug (Fig. 5G). NO rapidly reacts with ROS, forming peroxynitrites; therefore, we next scavenged them by adding MEG sulfate. MEG sulfate restored cell viability in GIT-27NO-treated but not in Saq-NO-treated (Fig. 5H) cultures, confirming the crucial role of NO-induced peroxynitrites in GIT-27NO-mediated toxicity.
Discussion

In our study, we demonstrated in two different colon cancer cell lines strong sensitivity to treatment with two compounds designed by covalent attachment of a NO moiety to the original anti-inflammatory or antiviral core drug. The mode of action of NO-modified drugs was profoundly altered compared with that of the original drugs. In agreement with previous data (Maksimovic-Ivanic et al., 2008; Mijatovic et al., 2008, 2010; Donia et al., 2009), the anti-inflammatory agent VGX-1027 did not affect colon cancer cell viability. Analyses of cell cycle distribution as well as AnnV-PI double staining revealed that GIT-27NO triggered apoptosis in both colon cell lines tested. However, in contrast to its action in Ta3H mammary cells, this process involves caspase activation as well as enhanced expression of caspases 8 and 3 at the gene level accompanied by mitochondrial membrane depolarization in mouse but not in Bax-deficient human colon cell lines (Mijatovic et al., 2010). Different intracellular profiles of the apoptotic process pulsed by the treatment as a reflection of intrinsic specificity of tested lines did not obviously
disturb the prevalence of the proapoptotic signal and completion of the dying process (Mijatovic et al., 2010). This cytotoxic mode of action coincided with a slight effect on the rate of cell proliferation that failed to influence the metastatic properties of either cell line when GIT-27NO was administered at subtoxic doses (not shown). As demonstrated previously, the cytoidal effects of GIT-27NO are related to the intracellular introduction of high levels of NO (Maksimovic-Ivanic et al., 2008; Mijatovic et al., 2010). Even if GIT-27 NO released lower amounts of NO compared with corresponding doses of exogenous NO donors, the uptake of NO in colon cancer cells exposed to GIT-27NO was impressively high. Subsequently, cell damage promoted by the toxic amount of NO released from GIT-27NO and other free radicals generated in this cascade were reflected in cell viability. Furthermore, the cytoidal effects of GIT-27NO on colon cancer cells were successfully blocked by the peroxynitrite scavenger MEG sulfate, confirming the crucial role of released NO and peroxynitrite in drug-mediated toxicity. Of interest, the intrinsic properties of HCT116 cells in redox status make them more tolerant to the oxidative stress generated by applied doses of GIT-27NO (Dang et al., 2005), thus requiring a prolonged period of exposure to the drug for induction of massive apoptotic cell death.

On the other hand, Saq-NO decreased the viability of colon cancer cells primarily through inhibition of cell proliferation but not through induction of cell death (Maksimovic-Ivanic et al., 2009). Moreover, a short pulse exposure of the colon cancer cells to Saq-NO was sufficient to induce irreversible loss of their dividing potential, indicating permanent changes in cell physiology. A long-lasting blockade in cell division was observed upon prolonged Saq-NO treatment, which significantly affected the metastatic potential of both cell lines independently of their previously documented differences in metastasis (Sahai and Marshall, 2003). We previously showed that permanent inhibition of cellular proliferation correlated with induction of differentiation and up-regulated p53 expression in cancer cells of neuroectodermal origin (Maksimovic-Ivanic et al., 2009). The phenomenon described was connected to p53 involvement in the process of differentiation of transformed cells. Strong up-regulation of p53 through de novo synthesis rather than disturbed proteo-
The contribution of NO, ROS, and RNS to the tumoricidal effects of the drugs. Cells (10⁴ cells/well) were treated with a range of doses of the indicated NO donors, Saq-NO, or GIT-27NO for 24 h, after which accumulation of nitrites was determined by the Griess reaction (A), and cell viability was examined by CV test (B). The data are presented as mean values and SD was less than 10%. Intracellular NO production was determined by DAF-FM indicator and ROS/RNI production by DHR staining. Intensity of fluorescence was analyzed by a Chameleon multiplate reader (C and D) or FACSCalibur flow cytometer (E and F). Cells were cultivated with IC₅₀ concentrations of the drugs in the presence of hemoglobin (Hb) (25 μM) (G) or MEG (100 μM) (H) for 24 h, and viability was measured by CV. The data are presented as the mean ± S.D. from a representative of three independent experiments *, p < 0.05, refers to untreated cultures.
litical degradation can be involved in decreased cellular proliferation and also lost of malignant properties. In concordance with our previous data, transient up-regulation of Akt phosphorylation was described in prostate cancer LNCap cells upon treatment with this drug (Mojic et al., 2012). The upstream regulator of S6 protein, S6K, regulates these processes (Fenton and Gout, 2011), offering an explanation for the decreased capacity of the cell lines tested to adhere, migrate, and invade. In addition, it was recently reported that Saq was able to inhibit metastatic properties through induction of angiogenesis and matrix metalloproteinase-2 and -9 expression (Sgadari et al., 2002; Toschi et al., 2011). Moreover, the results obtained in vitro were confirmed in a syngeneic metastatic model of colon cancer, in which pretreatment of CT26CL26 cells with Saq-NO for 24 h was sufficient to permanently affect their metastatic potential.

The absence of highly destructive RNS concurs with the cytosstatic mode of action of the compound (Calcerrada et al., 2011). It is evident that oxidative stress triggered by Saq-NO may not be triggered by the discrete quantity of NO released that probably falls within concentration ranges required by this gas to regulate cell physiology (Hickok and Thomas, 2010; Singh and Gupta, 2011). The efficacy of this newly synthesized drugs against colon cancer cells in tumor transplantation studies in animal cells is improving (Maksimovic-Ivanic et al., 2008, 2009; Mijatovic et al., 2008, 2010, 2011; Donia et al., 2009, 2011; Rothweiler et al., 2010; Canducci et al., 2011). Because NO is a short-lived and highly reactive molecule, the advantage of GIT-27NO over other NO donors is related to its ability to directly deliver NO into the cell and therefore prevent its loss before reaching a target. Moreover, rapid amplification of the toxic signal through formation of peroxynitrite makes it highly effective in inducing cell death.

In contrast to GIT-27NO, Saq-NO was created from a drug that already possessed anticancer properties. Addition of NO moiety to Saq markedly enhanced the anticancer action of saquinavir-NO, a novel nitric oxide-derivative of the protease inhibitor saquinavir, on hormone resistant prostate cancer cells. Cell Cycle 10: 225–229.


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