Gastrointestinal safety, chemotherapeutic potential, and classic pharmacological profile of NOSH-naproxen (AVT-219) a dual NO- and H₂S-releasing hybrid

Mitali Chattopadhyay¹, Ravinder Kodela¹, Pascale L. Duvalsaint¹ & Khosrow Kashfi¹,²

¹Department of Physiology, Pharmacology and Neuroscience, Sophie Davis School of Biomedical Education, City University of New York School of Medicine, New York, NY 10031
²Avicenna Pharmaceuticals Inc., New York, NY 10019

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Abstract
Naproxen (NAP) is a potent nonsteroidal anti-inflammatory drug (NSAID) with a favorable cardiovascular profile. However, its long-term use may lead to serious gastrointestinal and renal side effects. NOSH- (nitric oxide and hydrogen sulfide) releasing naproxen (NOSH-NAP, AVT-219) belongs to a new class of anti-inflammatory agents designed to overcome these limitations. We compared the gastrointestinal safety, anti-inflammatory, analgesic, antipyretic, and antiplatelet properties of AVT-219 to that of NAP in preclinical animal models. We also evaluated its anticancer effects in 11 human cancer cell (HCC) lines of six different tissue origins and in a chemotherapeutic xenograft mouse model of colon cancer. AVT-219: (1) was orders of magnitude more potent than NAP in inhibiting the growth of cultured HCC; (2) was safe to the stomach, whereas NAP caused significant ulceration; (3) showed strong anti-inflammatory, analgesic, antipyretic, and antiplatelet properties comparable to NAP; and (4) NAP caused a significant rise in plasma tumor necrosis factor-alpha (TNF), whereas in the AVT-219-treated rats this rise was significantly less. Mechanistically, AVT-219 was a strong antioxidant, inhibited cyclooxygenase (COX)-1 and -2, thus reducing prostaglandin (PG) E₂. In xenografts, AVT-219 significantly reduced tumor growth and tumor mass with no sign of GI toxicity, whereas NAP-treated mice died due to GI bleeding. AVT-219 displayed considerable safety and potency in inhibiting HCC growth; was an effective analgesic, antipyretic, antiplatelet, and anti-inflammatory; and was significantly more efficacious than NAP in reducing the growth of established tumors in a xenograft mouse model.

Abbreviations
ADT-OH, 5-(4-hydroxyphenyl)-3H-1,2-dithiole-3-thione; H₂S, hydrogen sulfide; LPS, lipopolysaccharide; MDA, malondialdehyde; NAP, naproxen; NO, nitric oxide; NOSH, nitric oxide and hydrogen sulfide; NSAIDs, nonsteroidal anti-inflammatory drugs; PGE₂, prostaglandin E₂; SNAP, S-Nitroso-N-acetyl-penicillamine; SOD, superoxide dismutase.

Introduction
Nonsteroidal anti-inflammatory drugs (NSAIDs) are the mainstay in the treatment of pain, fever, and inflammation. Unfortunately, their long-term use may lead to life-threatening side effects, mainly gastrointestinal, cardiovascular, and renal. The gastric damage is as a result of direct epithelial damage due to their acidic properties and also through the breakdown of mucosal defense mechanisms (leukocyte adherence, decreases in blood flow, and bicarbonate and mucus secretions) due to a reduction in mucosal prostaglandin (PG) biosynthesis as
a result of cyclooxygenase-1 (COX-1) inhibition (Wallace 1993, 2008). Among this class of compounds, naproxen is one of the most cardiovascular-safe drugs because of its sustained suppression of platelet thromboxane synthesis (Kearney et al. 2006) and is the one most often recommended for the treatment of osteoarthritis. However, it is notorious for causing gastrointestinal ulceration and bleeding.

Regular use of NSAIDs has been associated with lower incidence of cancer in general, the most compelling data available to date being that for colon cancer (Kune et al. 1988; Baron et al. 2003; Sandler et al. 2003; Rothwell et al. 2012). Unfortunately again, potentially life-threatening side effects alluded to above preclude their widespread use as chemopreventive agents (Wolfe et al. 1999), reviewed in Kashfi (2009). In our search for a “better NSAID”, we developed NOSH-NSAIDs (Kodela et al. 2012, 2013). These are regular NSAIDs, such as aspirin, naproxen, sulindac, and others, to which nitric oxide-(NO) and hydrogen sulfide- (H₂S) releasing moieties have been covalently attached. Both NO and H₂S are gaseous signaling molecules of biological importance (Li et al. 2016, 2017). The rationale for incorporating these gaseous mediators into NSAID molecules was based on the observations that NO (Brown et al. 1993; Wallace et al. 1994; Wallace and 2006; Predmore et al. 2012; King et al. 2014). The rationale for incorporating these gaseous mediators into NSAID molecules was based on the observations that NO (Brown et al. 1993; Wallace et al. 1994; Wallace and Miller 2000) and H₂S (Fiorucci et al. 2005; Wallace et al. 2007) have some of the same properties as PGs within the gastric mucosa, thus modulating some components of the local mucosal defense systems which should lead to reduced gastrointestinal toxicity.

In this study, we carried out a head-to-head comparison of the gastrointestinal safety, anti-inflammatory, analgesic, antipyretic, and antiplatelet properties of naproxen with those of AVT-219. We also evaluated the efficacy of naproxen and AVT-219 on established tumors in a xenograft mouse model of colon cancer.

Materials and Methods

Reagents

NOSH-naproxen (AVT-219) [6-(1-oxo-1-(4-(3-thioxo-3H-1,2-dithiol-5-yl) phenoxy) propan-2-yl) naphthalen-2-yl 4-(nitrooxy) butanoate] was synthesized as previously described (Kodela et al. 2013) and was a gift from Avicenna Pharmaceuticals Inc. (New York, NY). Its structural components are shown in Figure 1. Lipopolysaccharide (LPS) from Escherichia coli, naproxen, and carrageenan was purchased from Sigma (St. Louis, MO). The kits used for determination of PGE₂, lipid peroxidation, and superoxide dismutase (SOD) were purchased from Cayman Chemical (Ann Arbor, MI).

Experimental groups and treatments

In all the protocols described below, we used at least five male Wistar rats per group that weighed 180–200 g. The rats were obtained from Charles River Laboratories International (Wilmington, MA) and were fed standard laboratory chow and water ad libitum. The animals were housed in suspended, wire-bottom cages in a room maintained at 22 ± 2°C, humidity 65–70%, and 12-h light/12-h dark cycle. All experimental procedures were approved by our institutional animal research committees and were performed in accordance with nationally approved guidelines for the treatment of laboratory animals. It should be noted that in the anti-inflammatory and antihyperalgesia studies, the experimenter was blinded to the treatment protocols; whereas in all the other protocols the experimenter was not blinded.

Ulcer index

Rats were fasted for 48 h with free access to drinking water. Naproxen and AVT-219 at equimolar concentrations, 80 and 188 mg·kg⁻¹, respectively, were administered orally by gavage suspended in vehicle (0.5% carboxymethylcellulose, CMC). Six hours post administration, animals were euthanized in a CO₂ chamber; stomachs were then removed immediately, cut along the greatest curvature, and rinsed with ice-cold distilled water. The ulcer index (UI) was determined as described by Best et al. (1984) and reported by us previously (Chattopadhyay et al. 2010; Kodela et al. 2013). Excised tissues from each stomach were flash frozen in liquid nitrogen for assessing levels prostaglandin E₂ (PGE₂), malondialdehyde (MDA), and SOD activity. Blood samples from each rat were taken by cardiac puncture into heparin-containing vials and used for determination of plasma tumor necrosis factor-alpha (TNF-α).

PGE₂ levels

About 1 g of stomach tissue from each rat was homogenized in 5 mL of 0.1 mol/L phosphate buffer (pH 7.4)
containing 1-mmol/L EDTA and 10-μmol/L indomethacin. The homogenate was then centrifuged for 10 min at 12,000g at 4°C. PGE2 content in the supernatant was determined in duplicate using an enzyme immunoassay kit from Cayman Chemical, following the manufacturer’s protocol. Briefly, 50 μL each of standard or homogenate, enzymatic tracer, and specific antiserum were mixed. After overnight incubation at 4°C, the plates were washed with wash buffer, and Ellman’s reagent (200 μL) was then added to each well. After 1 h of incubation at room temperature, the absorbance was measured at 412 nm. PGE2 levels are expressed as pg mg⁻¹ of protein. Protein concentration was determined by Biorad assay.

**Lipid peroxidation**

Levels of MDA were measured as an index of lipid peroxidation using a colorimetric kit from Cayman Chemical, as detailed by the manufacturer and reported by us (Chattopadhyay et al. 2010). Snap frozen stomach tissue (25 mg) was sonicated for 15 sec at 40 V over ice with 250 μL of radioimmunoprecipitation (RIPA) buffer (25 mmol/L TrisHCl pH 7.6, 150 mmol/L NaCl, 1% NP-40, 1% sodium deoxycholate, and 0.1% SDS) with phenylmethylsulphonyl fluoride (PMSF) as protease inhibitor. Homogenates were centrifuged for 10 min at 200g at 4°C. Thiobarbituric acid reactant substances (TBARS) content was then measured in the supernatant and expressed as nmoles of MDA g⁻¹ of protein.

**SOD activity**

Using a colorimetric kit from Cayman Chemical, we measured SOD activity in the gastric mucosa by homogenizing 1 g of tissue in 5 mL of a buffer system containing 20 mmol/L HEPES (pH 7.2) with 1 mmol/L EGTA and 300 mmol/L of sucrose solution as reported previously (Chattopadhyay et al. 2010). SOD activity was measured spectrophotometrically at 460 nm and expressed as units (U) activity·mg⁻¹ protein. One unit of activity is defined as the amount of enzyme needed to exhibit 50% dismutaion of the superoxide radical.

**Plasma TNF-α level**

An enzyme immunoassay kit from R&D systems (Minneapolis, MN) was used to measure plasma TNF-α levels as reported by us (Chattopadhyay et al. 2010; Kodela et al. 2013). Briefly, fresh blood (50 μL) was incubated with antibodies specific for rat TNF-α and washed three times with assay buffer. Following washing of unbound antibody-enzyme reagent, substrate solution (tetramethylbenzidine, TMB, plus hydrogen peroxide) was then added. The reaction was stopped by adding dilute hydrochloric acid and its intensity measured at 450 nm. Sensitivity of this assay was determined by adding 2 standard deviations to the mean optical density value of 20 × zero standard replicates and calculating the corresponding concentration; sensitivity is estimated to be 1.6 pg·mL⁻¹.

**Antipyretic activity**

Rats received LPS (50 μg·kg⁻¹) intraperitoneally to induce fever 30 min after equimolar administration of naproxen (80 mg·kg⁻¹) or AVT-219 (188 mg·kg⁻¹) as described by Pinto et al. (1998). Rectal temperature was measured by inserting a lubricated thermistor probe (external diameter: 3 mm) 2.8 cm into the rectum of the animal. The probe was linked to a digital reader, which displayed the temperature at the tip of the probe (±0.1°C). Rectal temperatures were recorded hourly for 5 h.

**Determination of anti-inflammatory response**

Rats (n = 5 in each group) were administered vehicle (1%, CMC in 1 mL), naproxen (80 mg·kg⁻¹), or AVT-219 (188 mg·kg⁻¹) 30 min before inducing inflammation which was done by subcutaneously injecting carrageenan (1%, 100 μL, suspended in sterile saline solution) into the plantar surface of the right hind paw as described by Winter et al. (1962) and reported by us (Chattopadhyay et al. 2010; Kashfi et al. 2015). The change in paw volume before and after carrageenan injection was measured using a water displacement plethysmometer (Model 520; IITC/Life Sciences Instruments, Woodland Hills, CA) for 5 h. At the end of the experiment, rats were euthanized by asphyxiation in a CO2 chamber. After cutting each hindpaw at the level of the calcaneus bone, exudates (oedema fluid) were collected and processed for measurement of PGE2, as described above.

**Hyperalgesia**

Hindpaw inflammation was produced by intraplantar injection of carrageenan (100 μL of 1% carrageenan in sterile saline solution) into either hindpaw chosen at random. Suspensions of naproxen (80 mg·kg⁻¹), AVT-219 (188 mg·kg⁻¹), or vehicle (CMC, 0.5% w: v) were administered orally 1 h after carrageenan injection, and the mechanical nociceptive threshold determined 30 min after this and thereafter every hour for 5 h. The paw hyperalgesia was measured with an electronic pressure meter as reported earlier (Chattopadhyay et al. 2010; Kodela et al. 2013; Kashfi et al. 2015). The animals were
tested before and after treatments, the results are expressed by the delta reaction force (g).

**Antiplatelet activity**

Collagen-induced platelet aggregation of human platelet-rich plasma (PRP) occurs through a pathway dependent upon the arachidonic acid cascade (Nieswandt and Watson 2003). We therefore compared the antiaggregatory properties of AVT-219 to that of naproxen using this system as reported previously (Chattopadhyay et al. 2010; Kashfi et al. 2015). The antiaggregatory activity of the two compounds was determined as percent inhibition of platelet aggregation compared to control samples. IC\textsubscript{50} values were calculated by nonlinear regression analysis.

**COX enzyme activity**

The ability of AVT-219 to inhibit COX-1 and COX-2 enzymatic activity was compared to that of naproxen using a colorimetric COX (ovine, α-COX) inhibitor screening kit from Cayman Chemicals as described previously (Kulmacz and Lands 1983).

**Cell culture and MTT**

HT-29, SW-480, and HCT-15 human colon adenocarcinoma, MIA PaCa-2 and BxPC-3 human pancreatic cancer, LNCAP human prostate cancer, A549 human lung cancer, MCF-7 (estrogen receptor positive), MDA-MB 231 and SK-BR-3 (estrogen receptor negative) human breast cancer, and Jurkat T (human leukemia) cell lines were obtained from American Type Tissue Collection (Manassas, VA). All cell lines were grown as previously described (Kodela et al. 2012). Single-cell suspensions were obtained by trypsinization (0.05% trypsin/EDTA), and cells were counted using a hemocytometer. Viability was determined by the trypan blue dye exclusion method.

Cell growth inhibitory effect of naproxen and AVT-219 was measured using a colorimetric MTT assay kit (Roche, Indianapolis, IN).

**Therapeutic evaluation of NOSH-naproxen in a mouse xenograft model**

Male athymic nude (NU/NU) mice (n = 15), age 5 weeks, were purchased from Charles River Laboratories, Inc. After 1 week of acclimation, the mice were inoculated subcutaneously in the right flanks with SW480 human colon cancer cells (3 \times 10\textsuperscript{6}) suspended in Matrigel (50% v/v, BD Biosciences, San Jose, CA) using a 1-ml syringe and 22-gauge needles. When the tumors reached an average sizes of \textasciitilde 100 mm\textsuperscript{3} (10 days post inoculation), the mice were randomly divided into three groups and gavaged daily with either vehicle (0.5% CMC) or equimolar (0.18 mmol-kg\textsuperscript{-1}) concentrations of AVT-219 (100 mg-kg\textsuperscript{-1} body weight) or naproxen (45 mg-kg\textsuperscript{-1} body weight). Tumor size was measured every other day using electronic calipers, and the tumor volumes were calculated using the following formula: length \times width\textsuperscript{2}/2. After 30 days of treatment, the mice were sacrificed, the tumors collected, weighed, and photographed. Blood was also collected for determination of serum NO and H\textsubscript{2}S levels. The tumors were stored in formalin for immunohistochemistry studies.

**Immunohistochemistry**

All specimens were fixed in formalin and paraffin enclosed for examination. Five-micrometer-thick tissue sections were prepared to conduct immunohistochemistry using standard techniques as reported by us (Chattopadhyay et al. 2012). For proliferation we used primary mouse proliferating cell nuclear antigen (PCNA) at the appropriate dilution (1:100 dilution), and for detection of apoptotic cell death in tumor tissues, we used a TUNEL system kit from Promega (Madison, WI).

**Determination of plasma NO and H\textsubscript{2}S levels**

Plasma concentration of NO was quantified indirectly as the concentration of nitrate (NO\textsubscript{3}\textsuperscript{−}) and nitrite (NO\textsubscript{2}\textsuperscript{−}) by the Griess method using an assay kit from Cayman Chemical and following the protocol described by the manufacturer, as reported by us previously (Chattopadhyay et al. 2012; Kodela et al. 2012, 2013). Plasma was filtered using a 10-KD molecular weight cut-off filter from Millipore (Bedford, MA) before each analysis, to reduced background absorbance due to the presence of hemoglobin. After centrifugation for 10 min at 3000 rpm, samples (40 \mu L/well) were mixed with 10 \mu L nitrate reductase mixture and incubated for 3 h after which Griess reagents 1 and 2 (50 \mu L each) were added. Absorbance was read after 10 min at 540 nm using a plate reader. The concentration of nitrate/nitrite was calculated graphically from a calibration curve prepared from NaNO\textsubscript{2} standard solution.

H\textsubscript{2}S levels were measured as previously described using the standard methylene blue method (Li et al. 2007; Huang et al. 2010), and reported by us (Chattopadhyay et al. 2012; Kodela et al. 2012, 2013). Plasma (100 \mu L) was mixed with distilled water (100 \mu L), Zinc acetate (1\% w/v, 250 \mu L), trichloroacetic acid (10\% w/v, 250 \mu L), and N\textsubscript{5}, N\textsubscript{6}-dimethyl-p-phenylenediamine sulfate (133 \mu L,
20 µmol/L) in 7.2 mol/L HCl and FeCl₃ (133 µL, 30 µmol/L) in 7.2 mol/L HCl. The absorbance of the resulting mixture was determined after 15 min using a 96-well microplate reader at 670 nm. H₂S levels were calculated against a calibration curve of NaHS (1–250 µmol/L). Because of the strong acidic conditions, this method overestimates H₂S levels as it measures free H₂S, HS⁻ (hydrosulfide anion), S²⁻ (sulfide), acid-labile sulfide, and other, as yet unidentified, sulfides and can only provide a rough estimate of H₂S production (Olson 2009). Therefore, our results presented here indicate the sum total of these species.

**Data analysis**

All data are presented as the mean ± SEM, with sample sizes of at least 5 rats/mice in each group. Comparisons among groups were performed using a one-way analysis of variance followed by the Student t-test.

**Results**

**Naproxen, but not AVT-219, induced GI damage in rats**

Visual inspection showed that there were no gastric mucosal lesions in vehicle-treated rats (control group, Fig. 2A and D), for these rats, the gastric damage score (also described in the literature as “UI”) was zero (UI = 0). However, all rats treated with naproxen (80 mg·kg⁻¹) developed pronounced gastric ulcers and erosions, UI = 80 (Fig. 2B and D). In contrast, AVT-219 (188 mg·kg⁻¹) did not induce significant gastric damage UI = 2 (Fig. 2C and D). This is consistent with previously published data, where NO (Brown et al. 1993; Wallace et al. 1994; Wallace and Miller 2000) and H₂S (Fiorucci et al. 1994; Wallace and Miller 2000) were shown to act as mediators in mucosal defense.

**Gastric PGE₂ content**

The main products of cyclooxygenase-mediated arachidonic acid metabolism in the gastric mucosa are the PGs. In that respect, PGE₂ levels in the normal mucosal tissue of the vehicle-treated rats, the naproxen-treated rats, and the AVT-219-treated rats were 72.3 ± 4.2, 10.2 ± 1.6, and 22.1 ± 2.6 pg·mg⁻¹ protein, respectively (Fig. 3A). That is, a rat treated with naproxen (80 mg·kg⁻¹) produced about 86% less PGE₂ than rats in the control group. AVT-219 at an equimolar concentration (188 mg·kg⁻¹) reduced PGE₂ by about 70%. These comparative PGE₂ levels showed a clear and significant COX inhibition by naproxen and AVT-219.

**Effects of AVT-219 on suppression of COX activity**

When metabolized, AVT-219 should produce naproxen, H₂S, and NO. Previously, we had shown that NO and H₂S are released from AVT-219 (Kodela et al. 2013). In order to show the effects of the naproxen component, we compared the effects of AVT-219 to that of naproxen on pure ovine COX-1 and COX-2 enzymatic activity. As shown in Table 1, AVT-219 dose dependently and selectively inhibited the enzymatic activity of COX-1 more than that of COX-2. Naproxen at 3000 and 6000 µmol/L concentrations, inhibited COX-1 by 80 ± 4% and 92 ± 3%; and COX-2 by 65 ± 3% and 75 ± 2%. AVT-219 at 100 and 200 nmol/L inhibited COX-1 by 45 ± 3% and 54 ± 2%; and COX-2 by 16 ± 2% and 27 ± 3%. The concentrations of naproxen and AVT-219 chosen in these studies were based on their respective IC₅₀ for cell growth inhibition in SW480 colon cancer cell line (see below). We used indomethacin (1 µmol/L), a nonselective COX inhibitor (Riendeau et al. 1997), as a reference compound in these studies, which inhibited COX-1 by 69 ± 3% and COX-2 by 70 ± 2% (Table 1).

**Effect of AVT-219 on lipid peroxidation and SOD activity**

MDA levels representing oxidative stress in the gastric tissue were 6.5 ± 0.6 nmol·mg⁻¹ protein for the vehicle-treated group, this increased to 59 ± 3 nmol·mg⁻¹ in the naproxen-treated group, but was only 26 ± 2 nmol·mg⁻¹ protein in the AVT-219-treated group (Fig. 3B). On the other hand, SOD activity in the vehicle-treated group was 3.4 ± 0.5 U·mg⁻¹ protein, this was decreased to 1.4 ± 0.3 U·mg⁻¹ protein in the naproxen-treated group, and was significantly increased (compared to the naproxen group) to 3.6 ± 0.2 U·mg⁻¹ protein in the AVT-219-treated group (Fig. 3C).

**AVT-219 effectively reduces carrageenan-induced paw swelling**

Naproxen is very effective in treating inflammation and inflammatory pain. Here, we compared the COX-dependent anti-inflammatory activity of naproxen to that of AVT-219 using the carrageenan-induced rat paw edema model (Winter et al. 1962). After inducing inflammation, animals receiving vehicle showed a fast time-dependent increase in paw volume, which appeared to be plateauing toward the end of the experiment after 5 h (ΔV = 1.4 mL, Fig. 4A). In contrast, animals receiving naproxen and AVT-219 showed a weak inflammatory response (ΔV = 0.3–0.4 mL by 2 h), which decreased
over the next 3 h (Fig. 4A). From hours 3–5, AVT-219 was significantly \((P < 0.05)\) better than naproxen in its anti-inflammatory action (Fig. 4A). PGE2 is one of the main products of cyclooxygenase-mediated arachidonic acid metabolism and is a key mediator of the inflammatory process (Kashfi 2009). Comparison of PGE2 content of paw exudates showed a clear and significant COX inhibition by naproxen and AVT-219 (Fig. 4B). PGE2 level in control vehicle-treated rats was \(82 \pm 3 \text{ pg.mg}^{-1}\text{ protein}\), and in the naproxen- and AVT-219-treated rats were \(9.3 \pm 0.3 \text{ pg.mg}^{-1}\text{ protein}\) and \(32 \pm 2 \text{ pg.mg}^{-1}\text{ protein}\), respectively. This is equivalent to reduction of 89% and 61% by naproxen and AVT-219, respectively.

**Plasma TNF-\(\alpha\) levels are lower in AVT-219-treated rats**

The proinflammatory cytokine TNF-\(\alpha\) in plasma of naproxen-treated rats was increased by about 14-fold. Plasma TNF-\(\alpha\) levels were \(11 \pm 0.3 \text{ pg.mL}^{-1}\) in vehicle-treated rats and \(150 \pm 2 \text{ pg.mL}^{-1}\) in the naproxen-treated rats (Fig. 5). The corresponding value in

Figure 2. AVT-219 does not cause gastric damage. Naproxen (80 mg.kg\(^{-1}\)) and AVT-219 (188 mg.kg\(^{-1}\)) were administered orally at equimolar concentrations (0.35 mmol.kg\(^{-1}\)) and effects on the stomach were evaluated as indicated in “Ulcer index”. (A) Stomach of a vehicle-treated rat; (B) stomach of a naproxen-treated rat showing ulceration and bleeding; (C) stomach of a AVT-219-treated rat which is essentially devoid of ulcers; and (D) gastric damage due to naproxen, UI = 80 ± 5 mm \((^{+}\text{P} < 0.01 \text{ compared to vehicle})\), AVT-219, UI = 2 ± 0.4 mm \((^{*}\text{P} < 0.01 \text{ compared to naproxen})\).

Figure 3. Effects of AVT-219 and naproxen on gastric PGE2 level, lipid peroxidation (MDA), and superoxide dismutase (SOD). Three groups of rats were treated with vehicle, equimolar concentrations of AVT-219, and naproxen and their stomachs were removed and processed as described in “PGE2 levels”. AVT-219 and naproxen caused significant reductions in gastric mucosal PGE2 levels (A). Results are mean ± SEM of five rats in each group, \(^{*}\text{P} < 0.05 \text{ versus vehicle group}, ~^{\dagger}\text{P} < 0.05 \text{ versus AVT-219 group}. \text{Naproxen caused an almost nine fold increase in MDA levels, for AVT-219-treated rats, MDA levels were about 2.3-fold higher (B). Results are mean ± SEM for five rats in each group, \(^{*}\text{P} < 0.01 \text{ versus vehicle group, ~^{\dagger}\text{P} < 0.01 \text{ versus naproxen group}. \text{Naproxen caused a 2.4-fold reduction in SOD activity, whereas AVT-219 had no effect (C). Results are mean ± SEM of five rats, ~^{\dagger}\text{P} < 0.05 \text{ versus vehicle group, ~^{*}\text{P} < 0.01 \text{ versus naproxen group.}}

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AVT-219-treated rats was 50/C6/C3pg/C1/CmL/C0/C1, this represents a three fold reduction compared to the native compound.

Antipyretic activity of AVT-219

NSAIDs in general have a moderate antipyretic effect when administered orally. Here, we compared at equimolar doses (0.34 mmol·kg⁻¹) the effects of AVT-219 (188 mg·kg⁻¹) to that of naproxen (80 mg·kg⁻¹) on LPS-induced fever in rats. Both agents were administered (po) 30 min before injecting LPS (50 μg/kg ip). Vehicle-treated rats showed a time-dependent increase in body temperature (ΔT = 1.9 ± 0.1°C) which peaked at 3 h and then slowly declined by about 0.2°C over the next 2 h (Fig. 6A). Naproxen- and AVT-219-treated rats showed only about 0.3–0.4°C increase in body temperature within the first 30 min which fell down to 0.15–0.25°C by 1 h after LPS injection and continuously declined for the next 4 h, in fact at the end of the experiment the AVT-219-treated rats showed no detectable fever (Fig. 6A).

AVT-219 is an effective analgesic

This assay measures the ability of a test drug to reverse hyperalgesia (decreased threshold to a painful stimuli) produced by injection of carrageenan. The mechanical pain threshold was increased in a time-dependent manner after administering naproxen or AVT-219 (Fig. 6B). Pain threshold before administration of naproxen or AVT-219 ranged from 62 to 70 g. This was reduced to about 10 g after carrageenan injection confirming a higher sensitivity to mechanical stimuli (nonpainful at normal conditions). The mechanical threshold for pain increased to about 32 g in both naproxen- and AVT-219-treated groups.

Antiplatelet properties of AVT-219

Antiaggregatory effects of naproxen and AVT-219 were studied on collagen-induced platelet aggregation of human PRP. The results expressed as IC₅₀ are shown in Figure 6C. Analysis of the data, which represents the mean ± range of two independent studies performed in duplicate.

Table 1. AVT-219 inhibits cyclooxygenase enzyme activity.

| Treatment          | COX-1 % inhibition | COX-2 % inhibition |
|--------------------|--------------------|--------------------|
| NAP, 3000 μmol/L   | 80 ± 4             | 65 ± 3             |
| NAP, 6000 μmol/L   | 92 ± 3             | 75 ± 2             |
| AVT-219, 100 nmol/L| 45 ± 3             | 16 ± 2             |
| AVT-219, 200 nmol/L| 54 ± 2             | 27 ± 3             |
| Indomethacin, 1 μmol/L | 69 ± 3         | 70 ± 2             |

Pure ovine COX enzymes were treated with NAP or AVT-219 at their respective 1 × IC₅₀ and 2 × IC₅₀ for cell growth inhibition in SW480 colon cancer cell line for 15 min at 4°C after which ω-COX-1 and ω-COX-2 enzyme activity was determined. Results are mean ± range of two independent studies performed in duplicate.
itself to any statistical analysis; however, based on the ranges, there does not appear to be any differences between the two groups.

**AVT-219 inhibits the growth of various human cancer cell lines**

We evaluated the effects of naproxen and AVT-219 on the growth properties of eleven different human cancer cell lines of six different histological subtypes. The cell lines were that of colon (HT-29: COX-1 and COX-2 positive, HCT 15: COX-null, and SW480: COX-1 positive, low levels of endogenous COX-2), breast (MCF7: [ER (+)], MDA MB-231, and SKBR3: [ER(−)]); pancreatic (BxPC3: both COX-1 and COX-2 positive, MIAPaCa-2: COX-null), lung (A549), prostate (LNCaP), and T-cell leukemia (Jurkat). AVT-219 was very effective in inhibiting the growth of these cell lines (Table 2). The IC_{50}s for cell growth inhibition at 24 h for AVT-219 ranged from 0.09 ± 0.01 to 0.14 ± 0.02 μmol/L and that for naproxen was 200 ± 200 to 3110 ± 185 μmol/L. In a fold comparison of the IC_{50} values (naproxen/AVT-219), AVT-219 was at least 18,000-fold to 33,000-fold more potent than naproxen in various cell lines (Table 2). It should be noted that the data presented for HT-29, MCF-7, BxPC3, and Jurkat cells are replication of our previously published work (Kodela et al. 2013).

**Efficacy of AVT-219 in established tumor xenografts in nude mice**

Male athymic nude (NU/NU) mice were injected subcutaneously with SW480 colon cancer cells in the right flank, allowing for the development of subcutaneous tumors with an average volume of about 100 mm³ after 10 days. Following tumor formation, the mice were divided into three groups. The control group was treated with the vehicle (0.5% CMC); the other two groups were treated orally with equimolar (0.18 mmol/1 kg) concentrations of naproxen (43 mg/1 kg) and AVT-219 (100 mg/1 kg). All...
the mice treated with naproxen died within 2 weeks from what appeared to be severe GI bleeding and damage to the spleen and liver. However, the AVT-219-treated mice did not show any overt signs of toxicity, their average group weight was comparable to that of the controls. After 30 days of treatment (protocol shown in Fig. 7A), the AVT-219-treated mice (Figs. 7C and 8A) showed a considerable reduction in tumor growth compared with untreated mice (Figs. 7B and 8A). The stomachs of the AVT-219-treated mice were completely devoid of any GI erosions or bleeding (Fig. 7D). Compared with the control group with a mean tumor volume of $2100 \pm 380 \text{ mm}^3$, AVT-219-treated mice had a tumor volume of $370 \pm 50 \text{ mm}^3$, equivalent to a mean reduction of 82% ($P < 0.05$). Compared to the control group with average tumor mass $1.4 \pm 0.5 \text{ g}$, AVT-219 reduced the tumor mass to $0.63 \pm 0.11 \text{ g}$, equivalent to a reduction of 55% ($P < 0.05$) which was relatively consistent with continued regression of tumor growth over the same treatment period. Immunohistochemical analysis of AVT-219-treated and untreated mouse tumor sections was evaluated by PCNA, which is a biomarker for proliferation, and by TUNEL to determine the number of cells undergoing apoptosis. The vehicle-treated tumors showed a strong expression index for PCNA ($80 \pm 3\%$, Fig. 9A and C), whereas AVT-219-treated tumors showed a diminished expression of PCNA ($20 \pm 0.5\%$, Fig. 9B and C). TUNEL-positive cells in the vehicle-treated tumors were $1.5 \pm 0.4\%$ (Fig. 9D and F); AVT-219 increased apoptosis in the tumors ($83 \pm 3\%$) as measured by TUNEL staining for multiple tissue sections (Fig. 9E and F). Therefore, AVT-219 suppressed tumor growth by a combination of increased apoptosis and reduced cell proliferation.

AVT-219 releases both NO and H$_2$S in vivo

AVT-219 was designed to release both NO and H$_2$S. To that end, using in vitro and in vivo protocols, we had previously shown that indeed that was the case (Kodela et al. 2013). Here, using yet another in vivo model, that is, in the mice bearing the colon cancer xenografts, we have confirmed our previous finding showing that both NO and H$_2$S were significantly higher in the AVT-219-treated animals (Figure 10). It should be noted that the serum concentrations of H$_2$S as determined by the methylene blue method described in “Determination of plasma NO and H$_2$S levels” are not accurate, as this method is associated with considerable artifact (Olson 2009). What our data show are not absolute H$_2$S levels in the serum, but there appears to be an increase in some form of sulfide species (H$_2$S + HS$^-$ and S$^{2-}$ + others) that must clearly be due to the administered AVT-219.
In this study, we evaluated the effects of a novel NO- and H₂S-releasing derivative of one of the most commonly used NSAIDs, naproxen. AVT-219 exhibited all the classic pharmacological profiles of its native compound, the so-called four “A”s that is analgesic, antipyretic, anti-inflammatory, and antiplatelet aggregation. One of the most

**Figure 7.** Efficacy of AVT-219 in established tumor xenografts. Study protocol: (A) Male athymic nude mice were injected subcutaneously with SW480 colon cancer cells in the right flank, after 10 days average volume was about 100 mm³. Following tumor formation, the mice were divided into three groups and treated daily by gavage with the vehicle (0.5% CMC, B), or equimolar concentrations of AVT-219 (100 mg·kg⁻¹, C) or naproxen (43 mg·kg⁻¹). Naproxen-treated mice died within 2 weeks. (D) Stomachs of the AVT-219-treated mice showing no signs of GI erosions or bleeding.

**Figure 8.** AVT-219 reduced tumor growth and tumor mass. Animals were treated as depicted in Figure 7. Average tumor volume as function of time and tumor mass at sacrifice are shown in A and B, respectively. AVT-219 significantly reduced tumor growth from day 15 of treatment to sacrifice, *P < 0.01. Tumor mass was also significantly reduced by AVT-219 treatment, *P < 0.01. Naproxen-treated mice died within 2 weeks of treatment.

**Discussion**

In this study, we evaluated the effects of a novel NO- and H₂S-releasing derivative of one of the most commonly
significant side effects associated with naproxen is its GI toxicity, which limits its use. AVT-219 was designed to overcome this side effect and be a safer naproxen by releasing NO and H₂S, two gasotransmitters of physiological relevance that have been shown to be important mediators of gastric mucosal protection (Brown et al. 1993; Wallace et al. 1994, 2007; Wallace and Miller 2000; Fiorucci et al. 2005). In our comparative study at equimolar concentrations, AVT-219 did not produce any significant GI injury despite inhibiting mucosal PGE₂ synthesis, whereas naproxen caused a tremendous amount of GI bleeding. This GI injury is as a result of COX-1 inhibition. We further confirmed that both compounds dose dependently inhibited ovine COX-1 and COX-2 enzymatic activity in vitro. Our data clearly indicated that AVT-219 selectively inhibited COX-1 versus COX-2, whereas naproxen essentially inhibited both COX isoforms quite effectively. Another COX-1-mediated effect that we evaluated was the antiaggregatory effects of naproxen and AVT-219, which showed that both drugs had similar antiplatelet effects. On the other hand AVT-219 was just as effective as naproxen if not better in reducing LPS-induced fever, and exhibited potent anti-inflammatory properties using the carrageenan paw edema model, both of which are COX-2-mediated effects. Therefore, although in vitro AVT-219 selectively inhibited COX-1, its effects in vivo are consistent with actions that are mediated by both COX isoforms. In this regard there are two important observations to be made: one, it is important to exercise caution when applying in vitro data to any in vivo settings; two, as AVT-219 is more potent than naproxen in many of its actions, released NO and H₂S must contribute to its overall pharmacological properties.

Analysis of gastric tissue showed that naproxen reduced SOD activity by about three fold, whereas AVT-219 essentially had no effect on the activity of this antioxidative enzyme. This may explain in part the high levels MDA, an index of lipid peroxidation, seen in the naproxen-treated groups. We also observed that naproxen caused increases in the circulating levels of the proinflammatory mediator TNF-α, this may release oxygen-derived free radicals and proteases by triggering the adherence and activation of leukocytes, thus producing epithelial injury (Perini et al. 2004). It has been reported that leukocyte adherence is an early key event in the pathogenesis of mucosal injury associated with NSAIDs (Wallace 1993). Both NO (Wallace and Miller 2000) and H₂S (Zanardo...
et al. 2006), two components of AVT-219, are potent inhibitors of leukocyte adherence induced by NSAIDs, thus contributing to its GI safety profile.

Naproxen is often used to treat inflammatory conditions. We therefore compared the anti-inflammatory profile of AVT-219 to that of naproxen using the in vivo carrageenan-induced rat paw edema model. AVT-219 exhibited significantly better anti-inflammatory activity compared to naproxen. Of note is the observation that naproxen reduced PGE2 levels to a greater extent in the paw exudate compared to AVT-219, but that mice treated with equimolar concentrations of AVT-219 had better anti-inflammatory response. These observations suggest a strong role by NO and H2S, which we know are released by AVT-219 (Kodela et al. 2013), in modulating the anti-inflammatory response.

Naproxen is also employed in treatment of pain. We therefore compared the analgesic effect of AVT-219 to that of naproxen in an in vivo model of hyperalgesia (Chattopadhyay et al. 2010). Both drugs were equally effective in increasing the threshold response to a painful stimulus. These results are in line with our recent reports showing both NOSH-aspirin (Kodela et al. 2015) and NOSH-sulindac (Kashfi et al. 2015) to have equal analgesic efficacy to that of their respective native NSAID. The enhanced antinociceptive effect of AVT-219 may be due to its ability to reduce the production of proinflammatory cytokines, such as IL-1β, and restore neuronal sensitization caused by PGE2 through upregulation of KATP channels, as was observed with NOSH-aspirin but not with aspirin (Fonesca et al. 2015).

In United States, colorectal cancer (CRC) is one of the top three most common cancers in both men and women, resulting in an estimated 50,000 deaths this year alone (American-Cancer-Society, 2015). Epidemiological data show NSAIDs as the prototypical class of drugs that prevent CRC (Harris et al. 2005). While aspirin is the NSAID that has been investigated the most (Baron et al. 2003; Sandler et al. 2003; Rothwell et al. 2012), other NSAIDs including naproxen are also effective anticancer agents (Harris et al. 2008). In this study we first showed that AVT-219 was orders of magnitude more potent than naproxen in inhibiting the growth of adenomatous, epithelial, and lymphocytic cancer cell lines; that is, eleven cell lines originating from six different tissues. Thus, demonstrating a generalized property that was tissue-type independent. Recently we reported that this growth inhibition was as a result of reductions in cell proliferation, G0/G1 cell-cycle arrest, leading to increased apoptosis (Kodela et al. 2013). The underlying mechanism(s) for the enhanced potency of AVT-219 observed in these studies is not known, but must be due to contributions from both NO and H2S. While we do not know anything about the kinetics of NO and H2S release and their potential interactions, we do know that in vitro both contribute toward the potency of the intact molecule. This is based on our recent report where we showed that the biological activity of naproxen plus SNAP (releases NO) plus ADT-OH (releases H2S) was not as same as the biological activity of the intact NOSH-naproxen (AVT-219) molecule (Kodela et al. 2013), thus the sum of parts did not equal the whole. NO can also react with H2S to produce HSNO, which is a highly reactive intermediate (Filipovic et al. 2012; Cortese-Krott et al. 2015). Furthermore, NO and H2S signaling pathways appear to be intimately intertwined with mutual potentiation of biological responses (Cortese-Krott et al. 2015).

In this study, we also compared the efficacy of AVT-219 to that of naproxen at equimolar concentrations on established tumors using an in vivo xenograft mouse model of colon cancer. AVT-219 treatment resulted in large reductions in tumor volume and mass. Decrease in tumor size and mass was associated with inhibition of cell proliferation and induction of apoptosis. The dose of AVT-219 used in this mouse model was well tolerated with no apparent harmful side effects or overall gross toxicity; the mice in both control and AVT-219-treated groups had similar average body weights at necropsy and visual inspection of the organs did not show anything untoward. However, all the naproxen-treated mice died.

Figure 10. NO and H2S levels are increased in vivo after administration of AVT-219. Plasma concentration of NOx and H2S prepared at the end of the xenograft studies was quantified as described in “Determination of plasma NO and H2S levels”. Results are mean ± SEM for five mice in each group. *P < 0.001 versus vehicle.
by the end of the second week of treatment from what appeared to be GI bleeding and damage to other organs such as the spleen and the liver. In this regard, further work is necessary to establish the safe limit for long-term administration of naproxen in such an animal model and then compare its efficacy with equimolar concentrations of AVT-219.

In summary, AVT-219 retains all the classic therapeutic profile of native naproxen, such as the ability to inhibit inflammatory response, nociception, platelet aggregation, and fever, but spares the GI tract. It has all the attributes that make it an ideal promising alternative to existing therapies for the treatment of inflammation and pain. AVT-219 may also prove useful either alone or in combination with other classical chemotherapeutic agents in treatment of colon and possibly other cancers. Current work is directed toward unraveling the molecular targets of AVT-219 in different in vivo models of colon cancer and further evaluating its safety profile.

**Author Contributions**

*Participated in research design:* Kashfi, Chattopadhyay, and Kodela.

*Conducted experiments:* Kodela, Chattopadhyay, and Duvalsaint.

*Performed data analysis:* Kashfi, Chattopadhyay, Kodela, and Duvalsaint.

*Wrote or contributed to the writing of the manuscript:* Kashfi, Chattopadhyay, Kodela, and Duvalsaint.

All authors have read the final version of the manuscript and have approved its content for publication.

**Disclosures**

The authors have nothing to disclose except for K. K., who has an equity position in Avicenna Pharmaceuticals, Inc. to which NOSH-naproxen (AVT-219) has been licensed.

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