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The contribution of N$_2$O$_3$ to the cytotoxicity of the nitric oxide donor DETA/NO: an emerging role for S-nitrosylation

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Synopsis
The relationship between the biological activity of NO and its chemistry is complex. The objectives of this study were to investigate the influence of oxygen tension on the cytotoxicity of the NO$^\ast$ donor DETA/NO and to determine the effects of oxygen tension on the key RNS (reactive nitrogen species) responsible for any subsequent toxicity. The findings presented in this study indicate that the DETA/NO-mediated cytotoxic effects were enhanced under hypoxic conditions. Further investigations revealed that neither ONOO$^-$ (peroxynitrite) nor nitroxyl was generated. Fluorimetric analysis in the presence of scavengers suggest for the first time that another RNS, dinitrogen trioxide may be responsible for the cytotoxicity with DETA/NO. Results showed destabilization of HIF (hypoxia inducible factor)-1$\alpha$ and depletion of GSH levels following the treatment with DETA/NO under hypoxia, which renders cells more susceptible to DETA/NO cytotoxicity, and could account for another mechanism of DETA/NO cytotoxicity under hypoxia. In addition, there was significant accumulation of nuclear p53, which showed that p53 itself might be a target for S-nitrosylation following the treatment with DETA/NO. Both the intrinsic apoptotic pathway and the Fas extrinsic apoptotic pathway were also activated. Finally, GAPDH (glyceraldehyde-3-phosphate dehydrogenase) is another important S-nitrosylated protein that may possibly play a key role in DETA/NO-mediated apoptosis and cytotoxicity. Therefore this study elucidates further mechanisms of DETA/NO mediated cytotoxicity with respect to S-nitrosylation that is emerging as a key player in the signalling and detection of DETA/NO-modified proteins in the tumour microenvironment.

Key words: cytotoxicity, hypoxia, nitric oxide, S-nitrosylation

INTRODUCTION

NO is a stable-free radical with a relatively short half-life (seconds) in biological systems [1]. NO$^\ast$ is generated in tissues by the catalytic action of three main isoforms of NOS (nitric oxide synthase) enzyme on the amino acid, L-arginine. All three isoforms are known to be present in most tumours and are generally expressed at higher levels in tumours compared with their normal tissue counterparts [2]. It is well established that NO$^\ast$ plays a key role in the development, growth and malignant progression of cancer [3]. It also has a major influence on the response of the tumour to therapy [4]. NO$^\ast$ delivery by a variety of methods has been investigated as a potential therapeutic strategy against solid tumours, using both NO$^\ast$ donor drugs and various gene therapy strategies to target NO$^\ast$ to cancer cells [5,6]. Anti-tumour efficacy with minimal normal tissue toxicity has been a consistent feature of many studies following the systemic administration of NO$^\ast$ [4]. In biological systems, NO$^\ast$ rapidly reacts with other biological components [O$_2$•$^-$ (superoxide), O$_2$, thiols and metals] to form other secondary products that range from harmless metabolites [NO$_2$•$^-$ (nitrates) and NO$_3$•$^-$ (nitrates)] to the formation of more toxic related RNS (reactive nitrogen species). Therefore uncertainty remains around whether NO$^\ast$ contributes to cell
cytotoxicity directly or through its RNS. It has been suggested that the cytotoxic effects of NO$^*$ might be attributable to its RNS [7]. However, the mechanism by which NO$^*$ reactive metabolites exert their cytotoxicity within the tumour microenvironment has not been completely characterized.

One reaction product, ONOO$^-$ (peroxynitrite), has been implicated in numerous pathologies. ONOO$^-$ is a product of the reaction of NO$^*$ and O$_2^•$]$^•$$. This reaction occurs quickly because both NO$^*$ and O$_2^•$]$^•$ have valence electrons, so they combine together in a diffusion limited manner to form the oxidant (Supplementary Scheme S1 at http://www.bioscirep.org/bsr/033/bsr033e031add.htm Reaction 1). Almost all studies detail that ONOO$^-$ is a potent oxidant and its status has been strongly linked to various pathological conditions. It is also clearly described that ONOO$^-$ is formed at significant concentrations in tumours [8], yet the literature relating to its cytotoxic role in cancer is limited. Very few studies in cancer highlight this area, with most related to its role in mutation, inflammation and migration. There is also clear evidence that ONOO$^-$ is an apoptosis inducer [9]. Another RNS is HNO (nitroxylo), which may be a product of NOS or could be formed from the decomposition of RSNO (S-nitrosothiols) [10]. HNO is a potent cytotoxin that mediates double-strand DNA breaks via its oxidative intermediates. Studies using HNO donors have shown that HNO cytotoxicity is greater than NO$^*$ and is comparable with that of H$_2$O$_2$ and alkylhydroperoxide [11]. NO$^*$ could also react with O$_2$ to yield RNS such as NO$_2^*$ (Supplementary Scheme S1 Reaction 2) and N$_2$O$_3$ (dinitrogen trioxide) (Supplementary Scheme S1 Reaction 3). N$_2$O$_3$ generation requires oxidation of NO$^*$ first to NO$_2^*$, which will then combine with NO$^*$ to form N$_2$O$_3$. Although this reaction is very slow at physiological levels of NO$^*$, it has been suggested that the accumulation of both NO$^*$ and O$_2$ in hydrophobic areas associated with membranes and proteins may increase the probability of N$_2$O$_3$ formation [1].

Furthermore, high NO$^*$ fluxes under pathological conditions enable N$_2$O$_3$ formation, which regulates the function of many target proteins through the coupling of a nitroso moiety (NO$^*$$^•$) to a reactive cysteine, ultimately leading to the formation of RSNO, a process commonly known as S-nitrosylation [12] (Supplementary Scheme S1 Reaction 4). S-Nitrosylation plays an important part in the NO$^*$ physiological process and is considered to be a post-translational modification that plays a regulatory role in many protein functions, similar to phosphorylation.

Aberrant S-nitrosylation is associated with the pathogenesis of wide-ranging diseases, including cardiovascular, pulmonary, musculoskeletal and neurological disorders, as well as cancer [13]. The importance of S-nitrosylation in tumours is not fully understood. S-Nitrosylation of several pro-angiogenic proteins has been implicated in the progression of cancer such as HIF-1$\alpha$ (hypoxia-inducible factor 1$\alpha$), dynamin, Ras and COX2 (cylooxygenase 2) [14]. Conversely, RSNO have also shown potent anticancer properties: S-nitrosylated human serum albumin induced apoptosis and inhibited tumour cell growth in vitro and in vivo [15]. More recently, the anticancer properties of NO$^*$-NSAIDs (NO$^*$-aspirin and NO$^*$-naproxen) have been attributed to S-nitrosylation, and have also been shown to inhibit human colon cancer cell growth through suppression of NF-$\kappa$B (nuclear factor $\kappa$B) via S-nitrosylation of the p65 protein [16]. JS-K, a GST (glutathione transferase)-activated NO$^*$ donor has also shown inhibition of leukaemia cells via S-nitrosylation and degradation of nuclear $\beta$-catenin [17].

The purpose of this study was to determine the effects of oxygen tension and the key reactive intermediates of the NO$^*$ donor DETA/NO. In addition, the molecular mechanism of action and the emerging role of S-nitrosylation induced by DETA/NO were also investigated.

### MATERIALS AND METHODS

#### Chemicals

DETA/NO 2,2’-(hydroxynitrosohydrazono) bis-ethanimine (Sigma) was used in the NO$^*$ donor studies. With liberation of 2 moles of NO$^*$ per mole of compound and a half-life of 20 h at 37 °C, DETA/NO is ideal for the treatment of cells over a 24 h period. A 10$^{-3}$ M stock solution was freshly prepared in the cell culture medium with subsequent serial dilutions from 10$^{-3}$ to 10$^{-7}$ M. AS (Angeli’s salt) (Cayman) was used as HNO donor. It spontaneously dissociates in a pH-dependent, first-order process with a half-life of 2.3 min at 37 °C (pH 7.4). The salt was reconstituted in 0.1 M NaOH as 0.1 M stock solution, aliquoted, purged with inert argon gas and stored at −80 °C. Stock solutions were further diluted with PBS to prepare the required concentrations and quickly added to the cells for 10 min at the time of the experiment. Authentic solution of ONOO$^-$ (Calbiochem) was supplied in 4.7% (w/v) NaOH (160–200 mM). ONOO$^-$ was thawed rapidly, dispersed into 50 μl aliquots, purged with inert argon gas, frozen at −80 °C and protected from light. For experiments, 50 μl of stock solutions were thawed and further dilutions in PBS were made immediately prior to use. To determine the exact concentration, the absorbance of a 200 μl aliquot of each working solution was measured at $\lambda = 302$ nm ($\varepsilon = 1670$ M$^{-1}$·cm$^{-1}$). NaNO$_2$ and NaNO$_3$ salts (Sigma) were used in NO$_2^-$ and NO$_3^-$ studies, respectively. Both NaNO$_2$ and NaNO$_3$ salts were dissolved in the medium to obtain a range of concentrations which was consistent with values of NO$_2^-$ and NO$_3^-$ accumulated in the media following 24 h of DETA/NO treatment as determined by ion selective NO$_2^-$ and NO$_3^-$ electrodes (Supplementary Figure S1 available at http://www.bioscirep.org/bsr/033/bsr033e031add.htm). Ebselen, 4-hydroxy-3-methoxyacetophenone (Apocynin) and FeTPPS [5,10,15,20-tetraakis(4-sulfonatophenyl)porphyrinato fer(III)], chloride (Calbiochem) were used as ONOO$^-$ Scavengers. Ebselen and apocynin were dissolved in DMSO to give a stock solution of 100 and 600 μM, respectively, and stored at −20 °C. Stock solutions of ebselen and apocynin were further diluted to 10 and 300 μM, respectively. Control experiments previously confirmed that low concentrations of DMSO had no significant effect. FeTPPS was dissolved in distilled water to give a stock solution of 500 μM.
and stored at −20 °C. A stock solution of FeTPPS was further diluted to 50 μM concentration. Scavengers of RNS particularly N2O3, which include reduced L-GSH, ascorbic acid and sodium azide were obtained from Sigma-UK. N2O3 scavengers were dissolved in PBS, sterilized through a 0.2 μm filter and added to the cells at 1 mM concentration [18,19]. Scavengers were added to the cells 2 h before and throughout DETA/NO exposure.

Cell culture
All cells were purchased from the ATCC (American type culture collection) and were authenticated by the STR (short tandem repeat) profiling carried out by the suppliers. MDA-MB-231 breast cancer cells, DU145 human prostate cancer cells and L132 lung epithelial cells were cultured in DMEM (Dulbecco’s modified Eagle’s medium), Roswell Park Memorial Institute (RPMI) 1640 and MEM (minimum essential medium), respectively (In-vitrogen). All media were supplemented with 10% (v/v) foetal calf serum and 1% penicillin–streptomycin (Invitrogen) and cells were maintained in mono-layers in a tissue culture incubator at 37 °C with 5% (v/v) CO2/95% (v/v) air and sub-cultured every 3–4 days to maintain exponential growth.

NO* measurement
NO* is ultimately converted into NO2− and NO3−, which remain stable during cell culture and storage at −20 °C. The concentration of these two end products can be used to quantify NO* release from DETA/NO without the measurement problems caused by the transient nature of NO*. NO* levels were determined in the culture medium using ion-selective electrodes to independently measure NO2− and NO3− (Lazar Research Laboratories) at the specific time points according to the manufacturer’s instructions.

Clonogenic assay
Cells were seeded in 6-well plates at a density of 200/500 cells per well for MDA-MB-231 cells and 400/600 cells per well for DU145 and L132 cells. Seeded plates were incubated at 37 °C with 95% (v/v) air/5% (v/v) CO2 for 24 h before DETA/NO exposure. Clonogenic assays were performed under normoxia (21% O2) or 0.1% hypoxia using an Invivo2400 (Ruskinn Technology; Mid Glamorgan) hypoxic workstation for 24 h post-plating and before DETA/NO exposure. Following 24 h DETA/NO exposure, the fresh media were replaced and plates were then incubated for 7–14 days (dependent on the cell line) at 37 °C in 5% CO2/95% air and then colonies were fixed and stained with 0.4% crystal violet in 70% (v/v) methanol and counted using an automated colcount system (Oxford Optronics). 35 mm2 Glass Petri dishes (Sarstedt) were used for the anoxic experiment to exclude any oxygen that might be liberated from the plastic dishes [20].

Nuclear extraction
MDA-MB-231, DU145 and L132 cells were seeded in 150 cm2 plates either under normoxia or 0.1% hypoxia for 24 h post-plating, followed by treatment with LD50 values of DETA/NO.
either under normoxic or 0.1% hypoxic conditions. Aliquots of the protein homogenate were adjusted to achieve equal protein concentration and stored for Western blotting; the rest of the sample was processed to purify biotinylated proteins in order to test the protein of interest with the specific antibodies. Following re-suspension of the samples with washing buffer, 2 volumes of neutralization buffer [20 mM Hepes-NaOH, pH 7.7, 100 mM NaCl, 1 mM EDTA, 0.5% (v/v) Triton X-100] were added and biotinylated proteins were pulled down with 25 μl of packed streptavidin-agarose (Sigma) per mg protein for 1 h at room temperature (22°C). Beads were then washed three times with neutralization buffer containing 600 mM NaCl, incubated with elution buffer (20 mM Hepes–NaOH, pH 7.7, 100 mM NaCl, 1 mM EDTA, 100 mM 2-mercaptoethanol) for 20 min at room temperature. Aliquots from both the total fraction and the 2-mercaptoethanol eluate were separated by SDS/PAGE, and Western blot analysis was performed.

Determination of the total GSH levels

The total cellular GSH content was determined using a GSH assay kit (Cayman). As anticipated, S-nitrosylated GSH, GSNO (S-nitroso-glutathione), is not a substrate for GR (glutathione reductase) since the reducing thiol is no longer available for the GR catalysed enzymatic reduction of the reporting substrate [21]. Briefly, MDA-MB-231, DU145 and L132 cells were plated onto 90 cm² dishes and incubated overnight either at normoxic or 0.1% hypoxic conditions for cellular adherence. Cells were treated with LD₅₀ values of DETA/NO. Following each time point, cells were washed with ice-cold PBS, and processed according to the manufacturer’s instructions. All data were normalized to 1 mg of protein.

Fluorescent probes for measurement of N₂O₃ and HNO formation

Nitrosylation of cell permeable DAF-2DA (4,5-diaminofluorescein-diacetate) (Sigma) was used as a marker of nitrosative stress and N₂O₃ formation as previously shown [22]. MDA-MB-231, DU145 and L132 cells were plated onto black 96-well plates and left overnight for adherence. Cells were first loaded with 5 μM of DAF-2DA for 30 min at 37°C, DAF-loaded cells were washed followed by DETA/NO exposure (0.01 mM, 0.1 mM, 0.5 mM and 1 mM) for a specific time point under normoxia or 0.1% hypoxia. Plates were read using a fluorescence plate reader (FLUOstar OPTIMA; BMG LABTECH) with an excitation wavelength of 485 nm and a detection wavelength of 530 nm. The contribution of N₂O₃ to DAF-2DA fluorescence was also performed using DETA/NO or N₂O₃ scavengers. Cells were treated with DETA/NO (0.1 and 1 mM) ± nitrosylation quenchers (GSH, ascorbate and sodium azide) for 24 h either in normoxia or 0.1% hypoxia and fluorescence was measured as mentioned before.

In order to test whether HNO was formed following cellular exposure to DETA/NO, cells were probed with a pre-fluorescent probe TEMPO-9-AC [4-((9-acridinecarboxamido)-2,2,6,6-tetramethylpiperidin-1-oxyl] (Invitrogen), which has previously been used to detect HNO and to differentiate it from NO* [23]. A stock solution of TEMPO-9-AC (5 mM) was dissolved in acetonitrile, purged with nitrogen, stored as aliquots at −20°C and protected from light. Stock solutions were further diluted and used at 50 μM. MDA-MB-231, DU145 and L132 cells were plated onto black 96-well plates. After 24 h exposure to DETA/NO at the LD₅₀ dose, cells were washed twice with PBS and incubated with 50 μM of TEMPO-9-AC probe. After a 1 h incubation with the fluoroprobe at 37°C, fluorescence was measured using a plate reader at a wavelength of 430 nm.

Caspase-8 fluorimetric assay

MDA-MB-231, DU145 and L132 were plated in 90 cm² dishes and left overnight for adherence, followed by treatment with LD₅₀ concentrations of DETA/NO for 24 h either at normoxia or 0.1% hypoxia. Caspase 8 activity was assessed by caspase-8 fluorimetric assay kit (R and D systems), which uses a fluorogenic substrate AFC (7-amino-4-trifluoromethyl coumarin) as an indicator for caspase 8 enzyme activity.

Statistical analysis

All experiments were a minimum of three independent replicates with results expressed as mean ± S.E.M. Statistically significant differences were calculated using the two-tailed unpaired t test or one-way ANOVA with a P-value of ≤0.05 considered significant. Statistical analyses were performed using Prism 5.0 (GraphPad Software).

RESULTS

This study had two main objectives, the first to determine the influence of oxygen tension on the cytotoxicity of the NO* donor DETA/NO and the subsequent reactive intermediates responsible for this toxicity. The second aim was to investigate the molecular mechanism responsible for NO*-induced cytotoxicity under hypoxic conditions.

DETA/NO cytotoxic effects were enhanced under hypoxia

Decomposition of DETA/NO in solution involves the release of NO* (2 mol) and the originally reacted nucleophile (1 mol). In order to establish that the observed cytotoxic effects of DETA/NO were not due to the donor carrying moiety, we tested the cytotoxic effects of the DETA/NO carrier molecule (diethylenetriamine) in MDA-MB-231 cells. Different concentrations of DETA/NO were pre-incubated for 7 days in the cell culture medium at 37°C in order to ensure complete liberation of NO* prior to treating MDA-MB-231 cells with the spent donor. Cytotoxicity analysis of the accumulating nucleophile residue of DETA/NO showed no decrease in cell survival compared with the untreated controls (Figure 1A); therefore we concluded that the DETA/NO carrier molecule was inert in our studies. The cytotoxicity of the NO* releasing compound DETA/NO was examined in an
Emerging role for N2O3 to nitric oxide cytotoxicity

Our previous results demonstrate that cell survival under mild hypoxia (1 % O2) is similar to normoxic conditions, and 24 h exposure of cells to both 1 % O2 and 0.1 % O2 alone did not significantly affect survival in any of the cell lines (results not shown). There was variability in the cytotoxic potential of NO• between tumour cell lines and the normal immortalized cell line L132, which was significantly more resistant compared with the two tumour cell lines under similar treatment conditions. Exposure to DETA/NO under hypoxia at 0.1 % O2 was significantly more cytotoxic than in normoxia. The enhancing effect of hypoxia on DETA/NO-induced cytotoxicity was dose-modifying, albeit at higher DETA/NO concentrations. Treatment of cells with DETA/NO under anoxia produced significantly less cytotoxicity compared with 0.1 % hypoxia and normoxia (Figure 1B).

ONOO−, HNO and NO2−/NO3− formation are not prerequisites for DETA/NO cytotoxicity

In an attempt to determine the contribution made by toxic reactive intermediates of DETA/NO in cytotoxicity, we used specific scavengers of ONOO− (Ebselen, Apocynin and FeTPPs) in combination with the DETA/NO treatment. Each of these scavengers has a different mechanism to eliminate ONOO− formed following NO• exposure and is proven to protect against ONOO− cytotoxic effects [24–26]. Pre-treatment of MDA-MB-231 cells with the scavengers before treatment with DETA/NO for 24 h showed no significant difference in cell survival under normoxic or hypoxic conditions (Figure 2). The efficacy of TEMPO-9-AC as a probe for HNO was shown using different doses of AS. However, addition of the LD50 values of DETA/NO to MDA-MB-231, DU145 and L132 cells for 24 h left the TEMPO-9-AC fluorescence intensity unaffected both at normoxia and 0.1 % hypoxia (Figure 3A), indicating that HNO was not produced following the treatment with DETA/NO. Results also revealed that NO2− and NO3− are not the cytotoxic species following the treatment with DETA/NO (Figure 3B).
Figure 2 Clonogenic assay to determine the effects of the ONOO$^-$$^{-}$ scavengers Ebselen (EB 10 μM), FeTPPs (50 μM) and Apocynin (APO 300 μM) on cell survival following the treatment with DETA/NO under normoxia and 0.1 % (v/v) O$_2$

MDA-MB-231 cells were incubated under either normoxic or hypoxic [21 % (v/v) O$_2$ or 0.1 % (v/v) O$_2$] conditions for 24 h at 37 °C. ONOO$^-$$^{-}$ scavengers were added to the cells 2 h prior to the 24 h treatment with DETA/NO. Fresh medium was placed on the cells, which were then incubated for 2 weeks and then stained with 0.4 % crystal violet for colony counts. Data are the means of three independent experiments ± S.E.M. Statistical significance was calculated using a one-way ANOVA.

Contribution of N$_2$O$_3$ to DETA/NO cytotoxicity

DAF-2DA was used to assess nitrosylation potential of N$_2$O$_3$ because N$_2$O$_3$ rather than NO$^*$ nitrosylates DAF-2 to DAF-2 triazole [27] which can be measured by fluorescence. DAF-2DA does not react with NO$_2^-$, NO$_3^-$ or other RNS such as HNO or ONOO$^-$$^{-}$ which confers an element of specificity [28]. Our evaluation of DAF-2 against those species confirmed the finding of the previously mentioned study (Supplementary Figure S2 available at http://www.bioscirep.org/bsr/033/bsr033e031add.htm). DAF-2 triazole metabolite increased approx. 24-fold (depending on the cell type) under normoxia (Figure 4A). Although the reaction of NO$^*$ was slower under hypoxia than in the case of normoxia because of the lack of O$_2$ as a reactant, DAF-2 triazole was comparable under hypoxia following a 24 h incubation of 1 mM DETA/NO, resulting in an approximate 23-fold increase over control levels. This result was further confirmed by analysis of DAF-2 triazole fluorescent product in the presence of the N$_2$O$_3$ scavengers ascorbate, GSH and sodium azide. This resulted in equal abrogation of DAF-triazole formation under both oxygen concentrations (Figure 4B). Clonogenic survival studies using N$_2$O$_3$ scavengers clearly demonstrated that N$_2$O$_3$ contributed towards NO$^*$-mediated cytotoxicity evidenced by the rescue of clonogenicity (Figure 5). GSH and ascorbate were previously shown to scavenge N$_2$O$_3$ derived from IFN-γ (interferon γ), LPS (lipopolysaccharide)-stimulated ANA-1 macrophages [28] and sodium azide, a known NO$^+$ acceptor that has been shown to be a more specific scavenger for N$_2$O$_3$ [29].

RSNO formation following DETA/NO treatment

Protein S-nitrosylation was investigated using the biotin switch assay, which was validated in our study (Supplementary Figure S3 available at http://www.bioscirep.org/bsr/033/bsr033e031add.htm). This study is the first in vitro study that shows significant RSNO formation in cancer cells exposed to high NO$^*$ levels under hypoxia. Exposure of MDA-MB-231 cells to either HNO or ONOO$^-$$^{-}$ did not result in the formation of RSNO compared with controls. However, S-nitrosothiol formation increased following the treatment with DETA/NO (Figures 1 and 6). Pre-treatment of MDA-MB-231 cells with the N$_2$O$_3$ scavenger sodium azide followed by DETA/NO for 24 h under both oxygen conditions ablated the previous increase in S-nitrosothiol formation (Figures 2 and 6), which further supports the involvement of N$_2$O$_3$ in S-nitrosylation. Evidence from the nuclear extracts also revealed that S-nitrosylation occurs in the nucleus (Figures 3 and 6).

Quantification of GSH levels under 21 % O$_2$ and 0.1 % O$_2$

Results revealed that cells contain high GSH levels ranging between 5 and 6 mM dependent on cell type, and a slight decrease in GSH levels under 0.1 % hypoxia occurred only after 24 h (Figure 7, line graphs). Addition of the LD$_{50}$ values of DETA/NO showed a significant decline in GSH levels, which were time-dependent. A greater GSH reduction was evident in 0.1 % hypoxia compared with normoxia in the three tested cell lines (Figure 7, bar graphs).

DETA/NO induces greater apoptosis under hypoxia; involvement of both apoptotic pathways

In order to establish whether the increased DETA/NO-induced cytotoxicity at low oxygen tensions was a result of the intrinsic or extrinsic apoptotic pathway, the levels of key apoptotic proteins were analysed. The results indicate that DETA/NO-induced apoptosis was via both the internal and external pathways. Contribution of extrinsic apoptosis was confirmed by caspase 8 activation and Fas receptor up-regulation, which was more obvious.
Emerging role for N₂O₃ to nitric oxide cytotoxicity

Figure 3 Contribution of nitroxyl, nitrite and nitrate towards NO⁺-mediated cytotoxicity

(A) TEMPO-9-AC was used to detect HNO following cellular exposure to DETA/NO. MDA-MB-231, DU145 and L132 cells were treated with LD₅₀ concentrations of DETA/NO for 24 h under normoxic or 0.1% hypoxic conditions and the response compared with AS (10 μM–1 mM). Fluorescence was measured using a fluorescence plate reader with an excitation wavelength of 361 nm and a detection wavelength of 430 nm. Data were plotted as fold induction of TEMPO-9-AC-H relative to the controls. Data are the means of four independent experiments ± S.E.M. (B) Clonogenic assays to determine the effect of NO₂⁻, NO₃⁻ on cellular survival under normoxia, and 0.1% (v/v) O₂. Cells were incubated under either normoxic or 0.1% hypoxic conditions with different doses of NaNO₂ and NaNO₃ for 24 h at 37°C. Fresh medium was then placed on the cells, which were then incubated for 2 weeks and then stained with 0.4% crystal violet for colony counts. Data are the results of three independent experiments.
under 0.1 % hypoxia compared with normoxia (Figure 8). The three cell lines tested (Figures 9A–9C, and Supplementary Figure S4 at http://www.bioscirep.org/bsr/033/bsr033e031add.htm) showed the increased expression of the active forms of both the initiator caspase 9 and effector caspase 3 in a time-dependent manner and cleavage of PARP, an enzyme that is critical in cellular processes such as the repair of potentially lethal DNA damage. Cleavage of PARP has also been shown to be more significant under 0.1 % O₂ compared with 21 % O₂. Under normoxic conditions, only slight S-nitrosylation of caspases 9 and 3 was observed.

**DETA/NO treatment destabilizes HIF-1α and increases nuclear p53 and GAPDH protein expression**

In order to establish the signalling pathway responsible for the increase in apoptosis and cytotoxicity mediated by DETA/NO under hypoxia, we measured nuclear levels of the hypoxia-regulated protein HIF-1α, p53 and GAPDH post-treatment with LD₅₀ concentrations of DETA/NO at 8, 18 and 24 h under normoxia or 0.1 % (v/v) O₂ in MDA-MB-231, DU145 and L132 cells (Figures 10A–10C, and Supplementary Figure S5 at http://www.bioscirep.org/bsr/033/bsr033e031add.htm). Treatment of cells with DETA/NO resulted in significant HIF-1α accumulation compared with untreated cells at 21 % O₂, whereas treatment of cells with DETA/NO under 0.1 % hypoxia significantly abrogated the hypoxia-mediated increase in HIF-1α. Following the treatment with LD₅₀ concentrations of DETA/NO, accumulation of nuclear p53 increased with time under both 21 and 0.1 % (v/v) O₂ relative to untreated controls with the highest fold induction of p53 observed under 0.1 % O₂. Further investigation of key proteins for S-nitrosylation revealed that nuclear GAPDH was also S-nitrosylated.

**DISCUSSION**

Studies of NO• cytotoxicity under normoxia suggest that the presence of O₂ is a basic requirement for NO• toxicity. Stewart...
Emerging role for N$_2$O$_3$ to nitric oxide cytotoxicity

Figure 5 Dose–response curves showing survival of MDA-MB-231, DU145 and L132 cells following the exposure to various concentrations of DETA/NO, under both normoxic or 0.1 % hypoxic conditions + N$_2$O$_3$ scavengers ascorbic acid (AA; 1 mM), l-GSH reduced (GSH; 1 mM) and sodium azide (AZ; 1 mM)

Data are the mean of three independent experiments ± S.E.M. Statistical significance was calculated using a one-way ANOVA [$P = 0.003$, 0.044, 0.0001 for MDA-MB-231, DU145 and L132 cells, respectively, treated with DETA/NO + sodium azide under 21 % (v/v) O$_2$ compared with DETA/NO treatments; $P = 0.0001$ for MDA-MB-231, DU145 and L132 cells treated with DETA/NO + sodium azide under 0.1 % (v/v) O$_2$ compared with the DETA/NO treatments].

et al. [30] demonstrated resistance of PC-3 cells to cytotoxicity following treatment with the NO• donor NO-sulindac under low oxygen tensions [30]. Although most in vitro studies to date are focused on the radiosensitization or chemosensitization effect of hypoxic tumour cells by NO•, only very few studies postulate that the addition of NO• under hypoxia could have a synergistic effect [31,32] and only one study demonstrated this effect on a cancerous cell line (human fibrosarcoma cells) [32]. However,
the precise mechanisms by which the hypoxia conferred NO*-induced cytotoxicity have not been elucidated. The results from this paper indicate that 0.1% hypoxia showed the greatest enhancement of DETA/NO cytotoxic effects. However, L132 cells were rather resistant compared with MDA-MB-231 and DU145 cells, which could be attributed to a higher free-radical scavenging capacity of those cells (GSH levels were slightly higher in L132 cells compared with MDA-MB-231 and DU145 cells). McMurtry et al. [33] recently demonstrated that the NO* donor drug JS-K decreased the viability of breast cancer cell lines, but hardly affected the viability of normal mammary epithelial cells (HMEC-1). It was suggested in the study that higher expression of cellular defence enzymes by normal cells might protect against NO*-mediated cytotoxicity more than malignant cells, thus establishing selective cytotoxicity against malignant cells [33]. It is possible that GSH depletion particularly under 0.1% hypoxia renders cells more vulnerable to the cytotoxic effects of NO* in this study, which could be explained as a result of increased production of ROS (reactive oxygen species), or impaired GSH synthesis under hypoxia.

DETA/NO cytotoxicity was attributed to NO*-related reactive species rather than the direct cytotoxic effect of NO*, as cell survival increased whenever the source of O2 was withdrawn (anoxia). This result indicates the requirement of either O2 or (O2•−), for the formation of secondary oxidative species of NO* (Supplementary Scheme S1 Reactions 1–3).

Despite many studies implicating ONOO− as a key mediator of cell death following NO* exposure [34,35], these findings indicate that ONOO− is not a reactive intermediate in high NO* generating therapies. Furthermore, NO* reduction to HNO will not occur by simple electron transfer because of the low reduction potential of NO*, which has previously been determined to be approx. −0.5 V at pH 7 [36]. Consistently, our results indicate the absence of HNO with DETA/NO treatment, further evidenced by the lack of TEMPO-9-AC fluorescent metabolite following the treatment with DETA/NO. In addition, both NO2− and NO3− on their own did not show any particular cytotoxic effects in cells treated with NaNO2 and NaNO3 salts, therefore it is unlikely that NO2− and NO3− are the cytotoxic species following DETA/NO treatment.

As ONOO− formation requires both NO* and (O2•−), each of the reactants are produced at variable rates, which are dependent on environmental conditions. Therefore it is possible that the excess reactant could participate in further reactions. For example when (O2•−), is generated in excess of NO*, the formation of O2NOO− (peroxynitrate) (Supplementary Scheme S1 Reaction 5) is likely to be produced from the reaction of (O2•−), with *NO2. Other possibilities arise when NO* is generated up to three times faster than (O2•−), NO* reacts with *NO2 to form N2O3, which reacts quickly with any existing ONOO− to produce NO2− and two further molecules of *NO2 (Supplementary Scheme S1 Reaction 6). These *NO2 molecules can then further react with the

Figure 6  Biotin switch assay to determine the extent of protein S-nitrosylation following exposure to NO* and ONOO−

RSNO profile in MDA-MB-231 cells following the treatment with ONOO− (1 mM), AS (1 mM), or LD50 concentrations of DETA/NO under normoxia or 0.1% hypoxia (*), (2) or MDA-MB-231 cells treated with DETA/NO ± sodium azide. (3) The S-nitrosylated total protein profile in nuclear extracts following the treatment with LD50 concentrations of DETA/NO. Whole cell or nuclear lysates were subjected to the biotin switch method, biotin labelled nitrosoproteins were separated on SDS/PAGE (10% gel) and detected by Western blot analysis with an anti-biotin antibody. In parallel, β-actin or H2B protein levels served as a loading control. Images shown are the representative blots of three independent experiments. Arrows on the left point to visible bands representing the molecular mass of S-nitrosylated proteins.

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Emerging role for N₂O₃ to nitric oxide cytotoxicity

Excess NO• (for example, from a NO• donor drug) to form the potent nitrosating agent N₂O₃ facilitating further toxicity [37].

O₂•− is produced as a product of mitochondrial respiration due to the action of NOX (NADPH oxidase). Under normal conditions it is scavenged by SOD (superoxide dismutase); however, under hypoxic conditions particularly in tumours, O₂•− levels remain high because of the reduction in the scavenger SOD and the fact that NOX levels are elevated under these conditions [38]. This ensures that when CO₂ levels are elevated, the cytotoxic species N₂O₃ can be produced following DETA/NO treatment [18] (Supplementary Scheme S1 Reaction 7).

The results clearly suggest that the reactive intermediate N₂O₃ is responsible for the NO•-mediated toxicity at both low and high oxygen tensions. Although the precise mechanism of S-nitrosylation in cells is not well understood, the favoured reaction pathway for S-nitrosylation is produced from the reaction of N₂O₃ with a thiol (Supplementary Scheme S1 Reaction 4). This reaction becomes of greater relevance for S-nitrosothiol formation at higher NO• concentrations [18] since the latter are directly linked to the local N₂O₃ concentration in cells.

An elegant kinetic study by Lancaster [39] using GSH as a thiol model showed significant generation of RSNO with NO• concentrations exceeding 22.8 μM [39], which fits well with this study’s estimation of NO• liberation from DETA/NO. Our finding revealed that after 24 h of DETA/NO treatment at LD₅₀ concentrations, approx. 25 μM NO• were liberated as evidenced by accumulation of NO₂•− and NO₃•− levels. Further analysis of the fate of NO• liberated from DETA/NO can be elucidated by comparing the ratio of NO₂•− (marker of nitrosylation) to NO₃•− (marker of oxidation), which revealed higher NO₂•− to NO₃•− (12 NO₂•− : 1 NO₃•−) (Supplementary Figure S1). This is typical of N₂O₃-dependent S-nitrosylation.

Qualitative determination of RSNO revealed that a number of proteins were S-nitrosylated only when DETA/NO was added to cells. Some studies suggest that RSNO may be formed from ONOO−; however, <1 % of ONOO− was shown to produce RSNO in vitro [40]. Furthermore, relatively very few studies mention the formation of RSNO in an anaerobic environment [41,42], with all focusing on NOS-induced NO•. These studies indicate that the NO•-induced S-nitrosylation is abrogated in the presence of sodium azide. Therefore it can be concluded that the effect with DETA/NO is independent of either HNO or ONOO− and linked to N₂O₃ formation under both oxygen tensions.

Possible mechanisms of cytotoxicity

Examing the kinetics of both apoptotic pathways following DETA/NO exposure revealed induction of both the intrinsic and extrinsic apoptotic pathways. Activation of both initiator caspase 9 and effector caspase 3 were evident at earlier time points under 0.1 % (v/v) O₂, which indicates that the coupled effect of hypoxia and DETA/NO induced earlier apoptosis. PARP is an important enzyme involved in cellular processes such as cell death and DNA repair. Cleavage of PARP is associated with inactivation and apoptosis and has also been shown to correlate with caspase...
3 activation [43]. Cleavage of PARP was obvious in our results and again was present earlier when cells were exposed to both DETA/NO and 0.1 % O2. The present study concurs with previous reports [44] detailing the involvement of the intrinsic pathway of apoptosis following NO treatment. The potential implication of the extrinsic pathway of apoptosis was also evidenced by higher Fas expression levels and an increase in caspase 8 activity after 24 h DETA/NO treatment. This effect was also more obvious under 0.1 % hypoxia compared with normoxia, suggesting that the cellular stress induced by both DETA/NO and hypoxia augmented this pathway of apoptosis. The role of NO in Fas mediated apoptosis is still controversial with various studies confirming its role [45] and others disproving it [46]. Only recently Leon et al. [47] demonstrated that the
Figure 9 Evidence of activation of intrinsic apoptotic proteins following treatment with DETA/NO
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Figure 10 Western blot analysis of nuclear proteins (HIF-1α, p53 and GAPDH) expression over time under both normoxia and 0.1 % O2 hypoxia (A) MDA-MB-231, (B) DU145 and (C) L132 cells. Both S-nitrosylated and total proteins were examined as previously mentioned in Figure 9. Data were the mean densitometric values ± S.E.M. for three independent experiments and was plotted as fold change in protein expression normalized to controls over a time course of both 21 % (v/v) O2 normoxia and 0.1 % (v/v) O2 hypoxia.

Sensitization of cancer cells to Fas ligand induced apoptosis occurred after NO•-induced S-nitrosylation of cysteine residues in the cytoplasmic part of Fas receptor [47]. DETA/NO-induced apoptosis was first observed after 8 h with more pronounced effects by 24 h. This is a similar trend to the S-nitrosylation results which are in agreement with Duan and Chen [48] who detected increasing amounts of the total RSNO in cells undergoing apoptosis [48]. Conversely, it has been shown previously that S-nitrosylation of caspases prevents their activity and suppresses apoptosis [49]. This effect was observed in our study in untreated cells (a normal mechanism of pro-caspase existence in cells); however, the treatment with DETA/NO completely abrogated this effect. Therefore it is likely that the treatment with DETA/NO and the subsequent production of N2O3 up-regulates Fas expression known to denitrosylate caspases enabling apoptotic cleavage [50].

Caspase 9 and 3 (total and S-nitrosylated) and PARP cleavage over a time course following the treatment of MDA-MB-231 (A), DU145 (B) and L132 (C) cells with LD50 concentrations of DETA/NO under both normoxia and 0.1 % (v/v) O2 hypoxia. Data are the mean densitometric values ± S.E.M. for three independent experiments and are plotted as fold change in protein expression normalized to controls over a time course of both 21 % O2 normoxia and 0.1 % (v/v) O2 hypoxia. The asterisk indicates significant difference under 0.1 % (v/v) O2 hypoxia compared with normoxia for the total protein (*P ≤ 0.05, **P ≤ 0.005, ***P ≤ 0.0005 using a two-tailed unpaired t test).
Inhibition of the adaptive cellular response during hypoxia compared with normoxia as shown by destabilized HIF-1α transcription following the treatment with DETA/NO renders the cells more susceptible to NO• cytotoxicity. Previous studies have found that NO• destabilizes HIF-1α [51]. This could account for another mechanism of NO• cytotoxicity under hypoxia, where our data revealed that HIF-1α up-regulation was through S-nitrosylation. Furthermore, a significant increase in p53 observed over time under 0.1 % hypoxia compared with normoxia was consistent with other reports detailing that exposure to severe hypoxia (0.2 % O2) leads to p53 accumulation, and elevated apoptosis [52]. It was previously demonstrated that p53 is implicated in the degradation of HIF-1α [53]; therefore we speculate that overexpression of p53 under hypoxia may account for the loss of HIF-1α levels, which consequently promotes the induction of apoptosis under hypoxia compared with normoxia. Results in this study showed that p53 itself is a target for S-nitrosylation, which suggests that S-nitrosylation of p53 is essential for its activity towards induction of its downstream effectors of apoptosis. This observation could potentially be explained by the ten cysteine residues found in p53, two of which are particularly reactive (Cys182 and Cys277) [54]. However, it was recently reported that S-nitrosylation of p53 shows an inhibitory effect because of alteration in DNA binding [55], this represents the only study that detects S-nitrosylated p53, and clearly it remains to be experimentally confirmed whether S-nitrosylation of p53 and p53 accumulation contributes to cytotoxicity or apoptosis induced by N2O3. Nuclear S-nitrosylated GAPDH was shown recently to mediate NO•-triggered GAPDH apoptosis [56] and mediated nitrosylation of nuclear proteins, such as SIRT1 [57]. SIRT1 has been shown to block p53-induced apoptosis through p53 decetylation and induction of manganese SOD [58]. Its inhibition through nitrosylation could therefore potentiate p53 activity. S-Nitrosylation of GAPDH and its nuclear accumulation, as well as NOS-dependent apoptosis, were detected in thyroid carcinoma cells treated with TRAIL (TNF-related apoptosis-inducing ligand) and has been suggested that this mechanism contributes to the tumour-selective effects of TRAIL [59]. This represents the only study that used cancer cells for this type of investigation. Similar studies investigating the role of NO• in GAPDH-mediated cell death used NOS as a source of NO•. This approach could be used to mimic our donor drug in terms of sustained NO•. However, cumulative NO• concentrations were very low compared with the high μM concentrations of NO• produced by DETA/NO, which suggests that this mechanism takes place to mediate cell death under higher NO• fluxes associated with hypoxia-induced stress.

**CONCLUSIONS**

The data presented provides compelling evidence suggesting that NO• sensitizes tumour cells to hypoxia, mediated by an apoptotic mechanism involving down-regulation of HIF1α and that the cytotoxic intermediate is not ONOO− or HNO but rather N2O3. The data also highlight an emerging role of S-nitrosylation by N2O3 as a post-translational modification event that has an important role in NO•-induced cytotoxicity, and we showed that p53 itself might be a target for S-nitrosylation following the treatment with DETA/NO. Furthermore, S-nitrosylated GAPDH was detected, which may play a key role in DETA/NO-mediated apoptosis and cytotoxicity. Therefore this study elucidates further mechanisms of DETA/NO mediated cytotoxicity with respect to S-nitrosylation. This could shed the light on the diverse role and molecular mechanisms of NO•, which play a part in enhanced cytotoxicity under hypoxia, an effect that could be specifically targeted for therapeutic benefit.

**AUTHOR CONTRIBUTION**

Ahlam A. Ali performed much of the experimental work, manuscript and figure preparation. Jonathan A. Coulter assisted with experimental design, data interpretation and manuscript preparation. Claire H. Ogle contributed towards data collection. Marie M. Migaud provided input into various chemical reactions and manuscript preparation. David G. Hirst conceived the initial concept. Tracy Robson provided a critical appraisal of the project progression and assisted with manuscript preparation. Helen O. McCarthy provided full project supervision, expertise on NO• tumour biology and was central to compilation of the manuscript.

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**REFERENCES**

Emerging role for N2O3 to nitric oxide cytotoxicity


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SUPPLEMENTARY DATA

The contribution of N$_2$O$_3$ to the cytotoxicity of the nitric oxide donor DETA/NO: an emerging role for S-nitrosylation

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See the following pages for Supplementary Figures S1–S5 and Supplementary Scheme S1

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Figure S1  The levels of NO$^+$ in culture medium were indirectly determined using ion-selective electrodes to independently measure NO$_2^-$ and NO$_3^-$ at specific time points

MDA-MB-231, DU145 and L132 cells were incubated with 0.1 mM DETA/NO over time under 21% (v/v) O$_2$ and 0.1% (v/v) O$_2$ and reading was taken at specific time points. Data are the means of three independent experiments ±S.E.M. displayed as separate NO$_2^-$ and NO$_3^-$ readings. Total NO$_2^-$ and NO$_3^-$ were comparable under normoxia and hypoxia for the same dose, while comparing the ratio of NO$_2^-$ (marker of nitrosylation since all nitrosating intermediates metalizes to NO$_2^-$ at the end) to NO$_3^-$ (marker of oxidation since all oxidative intermediates metalizes to NO$_3^-$ at the end) revealed higher NO$_2^-$ to NO$_3^-$ (12 NO$_2^-$ : 1 NO$_3^-$).
Emerging role for N$_2$O$_3$ to nitric oxide cytotoxicity

Figure S2 DAF-2DA reactivity towards 1 mM of DETA/NO, AS (HNO donor), ONOO$^-$, NO$_2^-$, or NO$_3^-$

MDA-MB-231, DU145 and L132 cells were loaded with DAF-2DA, treated with aforementioned RNS for duration in accordance with their half lives, and fluorescence was measured using fluorescence plate reader with an $\lambda_{ex}$ of 485 nm and a detection wavelength of 530 nm. DAF-2 triazole fluorescent metabolite was due to N$_2$O$_3$ formed following cellular exposure to DETA/NO; therefore it is indirect measurement of N$_2$O$_3$.
Figure S3 Representative Western blot of the biotinylation profile in MDA-MB-231 cells following treatment with DETA/NO.
(A) Extracts from untreated or DETA/NO treated MDA-MB-231 cells were subjected to the biotin switch method after omitting one or two steps of the method. (B) To verify biotin labelling specificity for S-nitrosothiols, both the effects of omitting ascorbate and biotin in the assay are shown.

Figure S4 Representative Western blots of cytoplasmic extracts of (A) MDA-MB-231, (B) DU145 and (C) L132 cells quantified for total and S-nitrosylated apoptotic proteins via biotin switch assay.
Extracts were probed for caspase 9, 3 (total and S-nitrosylated) and PARP cleavage over a time course following the treatment with LD50 values of DETA/NO under both normoxia and 0.1 % (v/v) O2 hypoxia.
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Figure S5  Representative Western blots of nuclear proteins (HIF-1α, p53 and GAPDH) expression over time following the treatment with LD$_{50}$ values of DETA/NO under both normoxia and 0.1 % (v/v) O$_2$ hypoxia of (A) MDA-MB-231, (B) DU145 and (C) L132 cells.

Cells were quantified for the total and S-nitrosylated apoptotic proteins via the biotin switch assay.

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Scheme 1 Potential mechanisms for the production of various reactive nitrogen species generated from NO•

Reaction (1): the production of peroxynitrite (ONOO•−). Reaction (2): the production of nitrogen dioxide (NO2•). Reaction (3): the production of dinitrogen trioxide (N2O3). Reaction (4): the production of nitrosothiols (RSNO). Reaction (5): the production of peroxynitrate (O2NOO•−). Reaction (6): dinitrogen trioxide and peroxynitrite react to form two molecules of NO2. Reaction (7): when CO2 levels are elevated N2O3 can be generated in the presence of DETA/NO.