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**Detailed Terms**
Reactive nitrogen species regulate autophagy through ATM-AMPK-TSC2–mediated suppression of mTORC1

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Reactive intermediates such as reactive nitrogen species play essential roles in the cell as signaling molecules but, in excess, constitute a major source of cellular damage. We found that nitrosative stress induced by steady-state nitric oxide (NO) caused rapid activation of an ATM damage-response pathway leading to downstream signaling by this stress kinase to LKB1 and AMPK kinases, and activation of the TSC tumor suppressor. As a result, in an ATM–LKB1–TSC-dependent fashion, mTORC1 was repressed, as evidenced by decreased phosphorylation of S6K, 4E-BP1, and ULK1, direct targets of the mTORC1 kinase. Decreased ULK1 phosphorylation by mTORC1 at S757 and activation of AMPK to phosphorylate ULK1 at S317 in response to nitrosative stress resulted in increased autophagy: the LC3-II/LC3-I ratio increased as did GFP–LC3 puncta and acidic vesicles; p62 levels decreased in a lysosome-dependent manner, confirming an NO-induced increase in autophagic flux. Induction of autophagy by NO correlated with loss of cell viability, suggesting that, in this setting, autophagy was functioning primarily as a cytotoxic response to excess nitrosative stress. These data identify a nitrosative-stress signaling pathway that engages ATM and the LKB1 and TSC2 tumor suppressors to repress mTORC1 and regulate autophagy. As cancer cells are particularly sensitive to nitrosative stress, these data open another path for therapies capitalizing on the ability of reactive nitrogen species to induce autophagy-mediated cell death.

Significance

NO exposure triggered an ATM-mediated damage response in breast cancer cells involving activation of the LKB1 and TSC2 tumor suppressors, repression of mTORC1, ULK phosphorylation, and increased autophagic flux. The associated loss of cell viability indicates that autophagy can function as a cytotoxic response to nitrosative stress in tumor cells. Collectively, the data identify a nitrosative-stress signaling pathway that regulates autophagy. A more comprehensive understanding of signaling pathways regulating autophagy holds promise for developing new therapeutic approaches compromising pro-survival autophagic pathways that enable tumor cells to evade therapy, or promoting prodeath autophagic pathways that kill cancer cells.

Author contributions: D.N.T., R.C., L.J.T., C.L.W., and G.N.W. designed research; D.N.T., R.C., and L.J.T. performed research; D.N.T., R.C., L.J.T., A.R.T., R.S.S., C.L.W., and G.N.W. analyzed data; D.N.T., R.C., L.J.T., R.S.S., C.L.W., and G.N.W. wrote the paper; and A.R.T. developed the model in Fig 5.

The authors declare no conflict of interest.

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strong evidence that NO regulates autophagy, with implications both for understanding the physiological role of NO-induced signaling and the development of therapies that can modulate nitrosative stress to kill cancer cells.

**Results**

**Steady-State Exposure to Nitric Oxide Decreases Survival of MCF-7 Cells.** MCF-7 breast cancer cells were exposed to increasing NO cumulative doses from 0 to 2,488 μM min. This dose escalation was achieved by exposing cells in a reactor to a steady-state concentration of 11 μM NO for increasing lengths of time from 0 to 280 min. Twenty-four hours postexposure, cells showed decreased cell viability, compared with untreated controls, ranging from 27% to 40% after exposure to cumulative doses of NO from 1,244 μM min (140 min) to 2,488 μM min (280 min), respectively (Fig. 1A). Treatment of control cells with 5% CO₂:21% O₂:74% N₂ had no effect on cell viability. Importantly, the following evidence showed that decreased cell viability was not associated with increased apoptosis or programmed necrosis, suggesting rather that it was due to alternative cell death pathway(s): AnnexinV/PI staining and flow cytometry (Fig. 1B); cleavage of poly (ADP-Ribose) polymerase (PARP, a marker for apoptosis) (Fig. 1C); and exposures to NO in the presence or absence of the caspase inhibitor Z-VAD-FMK or the necroptosis inhibitor necrostatin-1 (Fig. S1 A, B, and C).

**Nitric Oxide Suppresses mTORC1 Signaling and Induces Autophagy.** We observed that the same steady-state (11 μM) NO exposure that induced cell death also suppressed mTORC1 signaling, as observed by reduced phosphorylation of p70/S6 kinase, 4E-BP1 (S6K and 4E-BP1 are direct targets of the mTOR kinase) and phosphorylation of S6 (downstream effector target of S6K) (Fig. 2A). Reduction in mTORC1 signaling occurred between 140 and 280 min exposure, at NO doses between 1,244 μM min (140 min) and 2,488 μM min (280 min). Comparable results were obtained when MCF-7 cells were treated with the NO donor spermine NONOate (SN), which similarly reduced phosphorylation of S6K and S6 in a time-dependent manner, with maxi-

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**Fig. 1.** (A) NO exposure leads to decrease in survival of MCF-7 cells. Cell viability was estimated following NO exposure at a steady-state concentration of 11 μM to attain the cumulative doses (622–2,488 μM min) presented on the x axis. Cell viability was measured by WST-1 assay 24 h after NO exposure and expressed as % of control. The data are represented as mean ± SD. (B) Steady-state NO exposure did not increase apoptosis in MCF-7 cells as observed by annexin-V staining. Emodin at a dose of 20 μM served as a positive control. (C) Western analysis with PARP antibody shows that exposure of MCF-7 cells to NO is not associated with the activation of PARP. Cells were exposed to NO at a steady-state concentration of 11 μM to attain the cumulative dose of 1,244 μM min, and lysates were prepared at 0 h, 24 h, 48 h, and 72 h postexposure. Staurosporine at the dose of 1 μM served as a positive control. LE represents light (short) exposure and DE represents dark (long) exposure of X-ray film.
mum inhibition 2–8 h after treatment and return to baseline at 16 h (Fig. S2A). A similar rebound to baseline was seen after removal of cells from the NO reactor; suppressed mTORC1 signaling in the presence of NO returned to baseline 8 h after removal from the reactor and remained at baseline for 24 h thereafter (Fig. 2B and Fig. S2B).

mTORC1 is a well-known negative regulator of autophagy. Recent reports indicate that mTORC1 and AMPK have opposing effects on autophagy mediated via phosphorylation of ULK1 at different regulatory sites (7). ULK1 is a key protein required for nucleation of the autophagosome and formation of the autophagosome membrane (11). Under optimal growth conditions, activated mTORC1 inhibits autophagy by direct phosphorylation of Atg13 and Unc-51-like kinase 1 (ULK1) at S757. This phosphorylation inhibits ULK1 kinase activity and subsequent autophagosome formation (12). However, under conditions of energy stress, AMPK suppresses mTORC1 via TSC and phosphorylates ULK1 at S757, initiating autophagosome formation and autophagy. As shown in Fig. 2B and C, mTORC1 phosphorylation of ULK1 at mTORC1 site S757 and increase in phosphorylation of ULK1 at AMPK site S317 in NO-treated MCF-7 cells. CT0 represents control (no NO) at 0 time point, and CT24 represents control at 24 h time point. LE represents light (short) exposure and DE represents dark (long) exposure of X-ray film.

Fig. 2. Steady-state NO exposure leads to repression of mTORC1. (A) Western analysis with p-S6K, p-S6, and p-4E-BP1 antibodies shows suppression of mTORC1 in NO-treated MCF-7 cells. (B) Restoration of mTORC1 activity after NO exposure when cells are incubated in normal culture condition. Time course study: cells were exposed to steady-state 11 μM NO for 140 min, and lysates were prepared after 0, 8, 16, and 24 h incubation in normal culture condition. Western analysis of p-S6K, p-S6, p-4E-BP1, p-ULK1 (S757), p-ULK1 (S317), p-AMPK, and total protein in MCF-7 cells. (C) Western analysis with p-ULK1 antibody shows decreased phosphorylation of ULK1 at mTORC1 site S757 and increase in phosphorylation of ULK1 at AMPK site S317 in NO-treated MCF-7 cells. CT0 represents control (no NO) at 0 time point, and CT24 represents control at 24 h time point. LE represents light (short) exposure and DE represents dark (long) exposure of X-ray film.
increased the ratios of LC3-II/LC3-I and LC3-II/GAPDH as determined by western analysis (Fig. 3A), indicative of increased autophagosome formation in response to mTORC1 repression. LC3-II to LC3-I ratios and LC3-II to GAPDH ratios remained elevated 24 h after cells were withdrawn from the NO reactor, suggesting that NO-induced autophagy persisted in these cells, possibly due to the continued presence of reactive nitrogen species formed during NO exposure (Fig. 3B).

To confirm that increased autophagosome formation was due to increased autophagic flux, cells were treated with Bafilomycin A1 (BafA1), which blocks lysosomal degradation of autolysosome contents. Efficacy of this treatment was confirmed by an increase in LC3-II levels in response to BafA1, with or without NO treatment (Fig. 3C and Fig. S3B). Similarly, whereas the long-lived protein and autophagy marker p62 decreased in response to NO, treatment with BafA1 abrogated this change, indicating that decreased p62 was due to increased autophagic flux as expected (Fig. S3B).

In addition, MCF-7 cells stably transfected with GFP-LC3 exhibited a significant increase in punctate cytoplasmic structures (autophagic vesicles) when treated with NO (Fig. 3D). Autolysosomes are also called acidic vesicles, reflecting the presence of acidic hydrolases that degrade vesicle contents (15). In response to NO, MCF-7 cells also showed an increase in acridine orange fluorescence associated with the presence of acidic vesicles and detected by flow cytometry (Fig. 3E).

Finally, Atg5<sup>+/+</sup> (autophagy-proficient) and Atg5<sup>−/−</sup> (autophagy-deficient) MEFs were used to confirm increased autophagy in response to NO (16). When cells of both types were treated with NO, increased LC3-II/LC3I ratio and degradation of p62 occurred only in autophagy-proficient cells (Fig. 3F and G), indicating dependence on autophagy for the observed responses to NO. Importantly, Atg5<sup>+/+</sup> cells were more sensitive to NO-induced cell death, exhibiting >70% cell killing in response to low levels of NO (622 µM/min), compared with autophagy-deficient cells, in which <20% loss in cell viability was induced by the same dose (Fig. 3H).

**NO Engages the ATM/LKB1/AMPK/TSC Signaling Pathway to Induce Autophagy.** Autophagy is an integral component of cellular damage responses to many types of stress, including nutrient deprivation, hypoxia, DNA damage, and oxidative stress. However, a mechanistic link between nitrosative stress and autophagy has not been described. Ataxia-telangiectasia mutated (ATM) is
a key serine/threonine protein kinase that acts as a cellular damage sensor, coordinating the cell cycle with damage-response checkpoints and DNA repair machinery to maintain genomic integrity (17). Several well-known targets for the ATM kinase include p53 and CHK2, both of which become phosphorylated in response to reactive oxygen or nitrogen species (10, 18, 19). Moreover, ATM also functions as a damage sensor in the cytoplasm via the recently described LKB1/AMPK/TSC pathway (10). Thus, we explored ATM and this downstream signaling pathway as a potential mechanism for NO signaling via mTORC1 and AMPK to induce autophagy.

Phosphorylation and activation of ATM (S1981) increased in cells under conditions of nitrosative stress in both the NO reactor (Figs. 2B and 4A), and in response to SN (Fig. S2C). Phosphorylation of

![Image](https://example.com/image)

Fig. 4. Involvement of ATM signaling in mTORC1 repression following NO exposure. (A) Western analysis with p-ATM, p-CHK2, p-AMPK, and p-ACC antibodies and their total protein counterparts shows activation of ATM and downstream effectors in MCF-7 cells exposed to NO. (B) Western analysis of ATM−/−, ATM+/−, and ATM+/+ MEF with p-S6K, p-S6, and p4E-BP1 antibodies shows that repression of mTORC1 by SN is ATM-dependent. (C) Western analysis of EBV-immortalized B-lymphocytes obtained from an AT (AT-B) patient and nonmutant individuals (WT-B) with p-ATM, p-S6K, and p-S6 antibodies shows that repression of mTORC1 by SN is ATM-dependent. (D) Western analysis with p-ATM, p-S6K, and pS6 antibodies in TSC2+/+ and TSC2−/− MEF shows that repression of mTORC1 by NO exposure is TSC2-dependent. CT, control.
Chk2 also increased concomitant with that of ATM, confirming activation of the ATM kinase (Fig. 4E). Importantly, in ATM-deficient MEFs (Fig. 4B and Fig. S4) and ATM-deficient human lymphoblasts (Fig. 4C), mTORC1 repression and induction of autophagy in response to NO was greatly attenuated (Fig. 4B and C and Fig. S4E). Interestingly, as reported for ROS-induced activation of ATM, dependence on ATM for repression of mTORC1 was lost with adaptation of ATM-null cells to tissue culture (10). Taken together, these observations indicate that ATM plays a central role in mTORC1 repression and autophagy induction in response to nitrosative stress.

When activated by either DNA damage or oxidative stress, ATM phosphorylates LKB1, the Peutz–Jeghers syndrome tumor suppressor, at Thr366, activating this kinase and its down-stream effector, AMPK (10, 20). Commensurate with ATM activation, we observed LKB1-dependent phosphorylation and activation of AMPK at T172 by nitrosative stress (Figs. 2B and 4A and Fig. S3C). AMPK activation was confirmed by phosphorylation of ACC at S79, a downstream target for the AMPK stress kinase (Fig. 4F and Fig. S3C). In contrast, as expected, mTORC1 repression and autophagy induction was not observed in LKB1-null HeLa cells under conditions of nitrosative stress (Fig. 4D and Fig. S4B). In addition to ACC, raptor was also phosphorylated by AMPK (Fig. 2B), suggesting that this inhibitory phosphorylation at S792 also contributed to mTORC1 repression.

An important down-stream target of AMPK is the TSC2 tumor suppressor, a “gatekeeper” for mTORC1 signaling that suppresses mTORC1 in response to energy stress (5, 21). Using TSC2 proficient (TSC2+/+) and deficient (TSC2−/−) MEFs, we observed a dependence on TSC2 for mTORC1 repression and induction of autophagy in response to nitrosative stress (Fig. S4C). As shown in Fig. 4E, although ATM was activated in response to NO in both cell types, mTORC1 repression occurred only in TSC2-proficient cells, indicating a requirement for TSC2 in this response. Notably, both TSC2+/+ and TSC2−/− MEFs are p53-deficient, indicating that p53 was not essential for repression of mTORC1 by NO.

The observed repression of mTORC1 and induction of autophagy described above is in contrast to a previous report from Sarkar et al., who, in 2011, reported that NO donors DETA NONOate and SIN-1 at high (500 μm) doses induced the opposite—mTORC1 activation—by nitrosative stress in both cell types, mTORC1 repression occurred only in TSC2-proficient cells, indicating a requirement for TSC2 in this response. Notably, both TSC2+/+ and TSC2−/− MEFs are p53-deficient, indicating that p53 was not essential for repression of mTORC1 by NO.

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Autophagy is a dichotomous phenomenon, involved in cell survival as well as cell death, depending upon both magnitude and cell context. Autophagy can promote cell survival by removing old or damaged cellular organelles and recycling key cellular building blocks for use in required metabolic pathways and construction of macromolecules. Cancer cells frequently use autophagy to survive nutrient deprivation induced by therapeutic agents. However, autophagy above a certain threshold can also induce cell death and, if triggered appropriately, can be used as a means of killing cancer cells. Interestingly, our data, showing that cell viability decreased in the presence of NO and that ATG5+/+ cells were more sensitive to NO cytotoxicity than ATG5−/− cells, suggest that autophagy is a prodeath response to nitrosative stress. Originally designated as type-II programmed cell death, autophagy can be a major death mechanism in cells that are resistant to apoptosis, as in settings of elevated BCI-2 activation or caspase-3 deficiency (24, 25). Breast cancer cells such as MCF-7 possess both of these properties and are resistant to apoptosis (26, 27). If these and other types of cancer cells are indeed particularly sensitive to induction of autophagy by nitrosative stress, this sensitivity suggests an opportunity to take advantage for designing cancer therapies that use nitrosative stress to induce cancer cell death. Future additional experiments to characterize the therapeutic index of “nitrosative stress therapy” may yield new insights into how to best exploit this phenomenon to develop more effective cancer therapies.

Materials and Methods

Cell Culture, Antibodies, and Reagents. MCF-7 cells [American Type Culture Collection (ATCC)] were grown in Improved Modified Eagle’s Medium (IMEM) supplemented with 10% (vol/vol) FBS and cultured in a humidified incubator at 37 °C with 5% CO₂. MCF-7 cells stably expressing GFP-LC3 were maintained in RPMI 1640 supplemented with 10% (vol/vol) FBS. TSC2+/− and TSC2−/− Mouse Embryonic Fibroblasts (MEFs) (kind gifts from Dr. D. Kwiakowski, Harvard Medical School, Boston, MA) and HeLa cells (ATCC) were grown in MEM supplemented with 10% FBS. ATM−/− human lymphoblasts (GM02184) and ATM−/+ human lymphoblasts (GM01526) were acquired fresh (from Coriell Repositories) for each experiment and maintained in RPMI 1640 supplemented with 15% FBS for less than four passages in culture. Primary fibroblasts ATM−/−, ATM−/+ and ATM+/+ cells derived from embryos at gestation day 13 were maintained in DMEM media with 15% FBS. Anti-S6K, anti-phospho-S6K (Thr389), anti-S6, anti-phospho-S6 (Ser235/240), anti-4E-BP1, anti-phospho-4E-BP1 (Thr37/46), anti-phospho-CHK2 (Thr68), anti-p53, anti-phospho-p53 (Ser15), anti-AMPK, anti-phospho-AMPK (Thr172), anti ACC, anti-phospho-ACC (Ser79), and anti-LC3 were purchased from Cell Signaling Technologies. Other antibodies used were anti-ATM (GeneTex), anti-TSC2 (Epitomics), anti-phospho-ATM (Ser1981) (Epitomics), and GAPDH and HRP-conjugated secondary antibodies. Other antibodies used were anti-4E-BP-1 (T37/46), anti-phospho-4E-BP-1 antibody (1:2,000 dilution), p-4E-BP-1 (T37/46) antibody (1:2,000 dilution), p-ACC (S-79) antibody (1:1,000 dilution), ACC antibody (1:1,000 dilution), p-AMPK (T172) antibody (1:500 dilution), AMPK antibody (1:500), p-ACC (S-79) antibody (1:1,000 dilution), ACC antibody (1:1,000 dilution), p-S6K (T389) antibody (1:500 dilution), S6K antibody (1:500 dilution), p-S6 (S235/236) antibody (1:2,000 dilution), S6 antibody (1:2,000 dilution), p-mTOR (Ser2448)-antibody (1:1,000 dilution), mTOR antibody (1:1,000 dilution), p-CHK2 (T68) antibody (1:1,000 dilution), CHK2 antibody (1:1,000 dilution), and LC3 antibody (1:1,000 dilution). The following day, they were probed with secondary anti-mouse or anti-rabbit IgG conjugated horseradish peroxidase antibody, and chemiluminescence was detected. As a protein loading control, membranes were stripped and reprobed with GAPDH antibody (1:5,000 dilution).

GFP-LC3 Localization. MCF-7 cells stably transfected with GFP-LC3 construct were plated on coverslips and exposed to nitric oxide in the NO delivery system. The cells were then fixed in 4% paraformaldehyde for 15 min at room temperature. Coverslips were mounted using Ultra Cruz Mounting Medium and examined in a Nikon Eclipse E600 fluorescence microscope for presence of autophagic puncta. The number of puncta per cell was determined and data were expressed as number of puncta per cell compared with unexposed GFP positive control or cells exposed to control gas.

Acidic Vesicle Detection. Detection and quantification of acidic vesicle formation during the process of autophagy was performed by acridine orange staining followed by flow cytometric analysis. In brief, MCF-7 cells were exposed to NO in the delivery system, incubated for 24 h in the incubator, harvested by trypsinization, washed twice with PBS, and then stained with acridine orange at a final concentration of 1 μg/mL for 30 min in the dark. Acridine orange is a weak base that can accumulate in acidic compartments, emitting bright red fluorescence, the intensity of which is proportional to the degree of acidity and/or volume of the compartment. Samples were then processed by flow cytometry using blue laser and 620/20 (AO-red) and 530/30 (AO-green) filters in a Be-Accuri Flow Cytometer.

Detection of Apoptosis. For determination of rate of apoptosis, cells were cultured as described above and exposed to NO (steady-state 11 μM) for various lengths of time, followed by 24 h incubation in a humidified incubator with 5% CO₂. Apoptosis was assessed by ApoAlert annexinV-FITC (fluorescein isothiocyanate) and propidium iodide (PI) apoptosis kit (Clontech) according to the manufacturer’s instructions. Briefly, cells were collected,
washed with PBS, resuspended in binding buffer provided, and stained with annexin V (5 μL) and PI (10 μL), and fluorescence was measured on a C6-Accuri Flow Cytometer.

**Detection of PARP.** MCF-7 cells were treated as above in the NO delivery system. Samples and matched controls were harvested at times 0, 24, 48, and 72 h posttreatment as follows. At 0 h, all cells were collected from the reactor supernatant and PBS washed by centrifugation for 5 min at 1,200 rpm. Lysis buffer (15 μL) was added to the pellet and added to the lysis buffer recovered from the cell culture dish. Samples were then treated as described in Immunoblotting. Medium and washes collected from time points 24, 48, and 72 h were centrifuged and added to the lysis buffer collected from the cell culture dishes. In this process, all cells living and dead are collected and processed for PARP cleavage determination.

**Statistical Methods.** All data are represented as mean ± SD. The statistical analysis was performed by SAS statistical software. The quantitative analysis of Western data was represented as the percentage of fold change from control. Using this fold-change value, a one-sample, one-sided t test was performed to determine whether the percent change from control was higher than 100%. This same method was used for each experiment examining LC3-II with the respective controls. Similarly, fold change in p62 was calculated and was analyzed with a one-sample, one-sided t test to determine whether the fold change was less than 100%. The GFP-LC3 puncta count was compared between control and NO treated group using a one-sided paired t test. Any P values less than 0.05 were considered statistically significant.

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