ATM inhibition drives metabolic adaptation via induction of macropinocytosis

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Macropinocytosis is a nonspecific endocytic process that may enhance cancer cell survival under nutrient-poor conditions. Ataxia-Telangiectasia mutated (ATM) is a tumor suppressor that has been previously shown to play a role in cellular metabolic reprogramming. We report that the suppression of ATM increases macropinocytosis to promote cancer cell survival in nutrient-poor conditions. Combined inhibition of ATM and macropinocytosis suppressed proliferation and induced cell death both in vitro and in vivo. Supplementation of ATM-inhibited cells with amino acids, branched-chain amino acids (BCAAs) in particular, abrogated macropinocytosis. Analysis of ATM-inhibited cells in vitro demonstrated increased BCAA uptake, and metabolomics of ascites and interstitial fluid from tumors indicated decreased BCAAs in the microenvironment of ATM-inhibited tumors. These data reveal a novel basis of ATM-mediated tumor suppression whereby loss of ATM stimulates protumorigenic uptake of nutrients in part via macropinocytosis to promote cancer cell survival and reveal a potential metabolic vulnerability of ATM-inhibited cells.

Introduction

Macropinocytosis is a nonselective endocytic process whereby cells take up fluid, macromolecules, metabolites, and other cargo from the surrounding microenvironment (King and Kay, 2019; Palm, 2019; Zhang and Commisso, 2019). Many studies have evaluated the critical role of macropinocytosis as a nutrient-scavenging mechanism in cancers under nutrient-deprived conditions (Commisso et al., 2013; Davidson et al., 2017; Hodakoski et al., 2019; Kamphorst et al., 2015; Kim et al., 2018; Lee et al., 2019; Redelman-Sidi et al., 2018; Tejeda-Munoz et al., 2019; Yao et al., 2019). These studies have mainly focused on cancers with high PI3K activity, such as those with mutant RAS or phosphatase and tensin homolog (PTEN) loss, which act upstream of the Rac1-Pak1 actin remodeling pathway to promote macropinosome formation (Zhang and Commisso, 2019). Recent studies suggest that the signaling to promote macropinocytosis, which merges at the activation of Rac1, is more complex (Hobbs and Der, 2022), and other tumor-associated pathways, such as HIF1 and NRF2, have recently been shown to promote macropinocytosis (Su et al., 2021; Zhang et al., 2022). One central nutrient-sensing pathway that is linked to macropinocytosis is the mTORC1 pathway (Palm, 2022). mTORC1 is a master regulator of cell growth, proliferation, and macromolecule synthesis (Kim and Guan, 2019; Saxton and Sabatini, 2017). mTORC1 activity is regulated at many levels, including an abundance of the branched-chain amino acids (BCAAs) leucine and isoleucine (Foster and Fingr, 2010). Studies have shown that the downregulation of mTORC1 promotes macropinocytosis (Dai et al., 2021; Dendo et al., 2018; Sung et al., 2015). This would presumably restore energy homeostasis through the uptake of free amino acids, extracellular proteins, or other nutrients.

Ataxia-Telangiectasia mutated (ATM) is a tumor suppressor, and mutation or loss of ATM expression promotes genomic instability and predisposes cells to tumorigenesis (McKinnon, 2004, 2012). While ATM is important for the response to DNA double-strand breaks (Shiloh, 2003), it is also known to play a role in cellular metabolism (Dahl and Aird, 2017; Guleria and Chandna, 2016). We previously demonstrated that ATM is wild type, and its signaling is upregulated in ovarian cancer (Chen et al., 2020). We also found that ATM expression is inversely correlated with metabolic gene signatures in ovarian cancer patient specimens. Furthermore, we and others have shown that the inhibition of ATM increases the uptake of glucose and glutamine to provide nutrients for cell growth and proliferation (Aird et al., 2015; Dahl and Aird, 2017). Our previous results

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suggest that inhibition of ATM reprograms metabolism through the suppression of p53 signaling and enhanced c-MYC protein stability (Aird et al., 2015). Indeed, these and other models where ATM suppression or mutation has been shown to alter cellular metabolism are in cells with WT p53 and normal c-MYC expression. Whether ATM similarly alters nutrient uptake and cellular metabolism in the context of cancers with mutated p53 and high c-MYC expression is unclear. Moreover, ATM inhibitors are currently undergoing clinical trials (Jin and Oh, 2019), although they are not generally effective as a mono-therapy (Batey et al., 2013; Chen et al., 2020; Fujimaki et al., 2012; Golding et al., 2012; Jin and Oh, 2019; Riches et al., 2020). Thus, understanding how the inhibition of ATM drives metabolic reprogramming may be important toward identifying potential resistance mechanisms or other targets that could be used in combination with these inhibitors in ATM-WT tumors.

Here, we found that the suppression of ATM increases nutrient uptake in p53 mutated and c-MYC-amplified cancer cells even upon a single knockdown of key transporters. This nonspecific nutrient uptake under nutrient-poor conditions occurred in part via macropinocytosis. Underscoring the importance of this pathway in ATM-inhibited cells, suppression of macropinocytosis significantly inhibited the proliferation of cancer cells both in vitro and in vivo. Analysis of metabolites suggested increased uptake of BCAAs in ATM-inhibited tumors and cells, and supplementing cells in vitro with exogenous BCAAs decreased macropinocytosis. Together, these data demonstrate that inhibition of ATM reprograms cellular metabolism in part via induction of macropinocytosis and reveal that macropinocytosis is a vulnerability of ATM-inhibited tumors.

Results and discussion

Inhibition of ATM kinase activity increases glucose and glutamine consumption in a transporter-independent mechanism

ATM loss or inhibition alters whole-body and cellular metabolism (Aird et al., 2015; Cosentino et al., 2011; Dahl and Aird, 2017; Guleria and Chandna, 2016; Valentín-Vega et al., 2011). We previously published that an increased uptake and consumption of glucose and glutamine, two carbon sources that are critically important for cancer cell metabolism, is in part due to the in-activation of p53 and increased c-MYC stability downstream of ATM knockdown (Aird et al., 2015). However, the transporter-dependence of nutrient uptake in ATM-inhibited cells has never been directly tested. To answer this question, we used three ovarian cancer cell lines with functional/WT ATM and differential status of p53 and c-MYC (Ovcar8: mutant p53, c-MYC amplification; Ovcar3: mutant p53; Ovcar10: het mutant p53) and tested glucose and glutamine uptake upon inhibition of ATM in nutrient-limiting conditions. These conditions were chosen as replete media often masks metabolism-mediated effects and does not faithfully recapitulate the nutrients observed in tumors in vivo (Cantor, 2019). Ovarian cancers have activated ATM signaling, and therefore, inhibition of ATM is being explored as a therapeutic strategy in these and other solid tumors (Chen et al., 2020; Jin and Oh, 2019; Weber and Ryan, 2015). We found that pharmacological inhibition of ATM kinase activity using two different small-molecule inhibitors (KU60019 and AZD0156), both of which decrease Chk2 phosphorylation (Fig. 1 A and Fig. S1 A), increased glucose and glutamine consumption in the ovarian cancer cell lines regardless of p53 or c-MYC status (Fig. 1, B and C; and Fig. S1, B–D). Interestingly, knockdown of the glucose transporters SLC2A1/GLUT1 and SLC2A4/GLUT4 or the glutamine transporter SLC1A5/ACST2 did not respectively alter the glucose or glutamine uptake induced by ATM inhibition (Fig. 1, D–G), although knockdown did suppress uptake of metabolites in parental cells (Fig. S1, E and F). Although compensation through other transporters is possible, these data suggest another mechanism may also be contributing to metabolic uptake in these cells.

Inhibition of ATM kinase activity induces macropinocytosis

Previous studies have shown that macropinocytosis is one mechanism whereby cancer cells scavenge nutrients from the microenvironment to support survival and proliferation under nutrient-poor conditions (Commissio et al., 2013; Davidson et al., 2017; Hodakoski et al., 2019; Kamphorst et al., 2015; Kim et al., 2018; Lambies and Commissio, 2022; Lee et al., 2019; Palm, 2019; Palm et al., 2017; Recouvreux and Commissio, 2017; Redelman-Sidi et al., 2018; Yao et al., 2019; Zhang and Commissio, 2019). Macropinocytosed nutrients are transported within the macropinosome to the lysosome where the engulfed macromolecules may be degraded (King and Kay, 2019; Palm, 2019) and released into the cytoplasm by specific permeases on the lysosome membrane (Perera and Zoncu, 2016), which are different than the cell-surface-bound transporters. In nutrient-limiting conditions, 24 h of cotreatment of cells with the ATM inhibitor and 5-(N-ethyl-N-isopropyl)-amiloride (EIPA), a Na+/H+ exchanger that is an inhibitor of macropinocytosis (Commissio et al., 2014; Ivanov, 2008), decreased consumption of glucose and glutamine (Fig. S2 A). Therefore, we aimed to confirm these results using a fluorescently labeled 70 kD dextran. Due to its large size, 70-kD dextran is used as a surrogate for macropinocytosis as it cannot be taken up through other endocytic pathways (Commissio et al., 2014; Ivanov, 2008). While the inhibition of ATM in complete media did not increase dextran uptake after 2 h treatment, we did observe an increase under starvation (basal media) conditions (Fig. 2, A–D; gating strategy Fig. S2 B; media conditions detailed in Materials and methods). This medium was chosen because we reasoned that limiting extracellular metabolites may help to promote the macropinocytosis process. Other nutrient-limiting media had a similar effect (Fig. S2 C). A different ATM inhibitor and ATM knockdown using shRNA also increased dextran uptake (Fig. S2, D–F). To address the possibility that FITC fluorescence may be affected by low pH when macropinosomes fuse with lysosomes (Chen et al., 2008), we performed a time course experiment. A significant increase in dextran uptake was observed starting as early as 15 min with a peak at 1 h (Fig. S2 G). While the signal is still high at 90 min and 2 h, we do start to see a decrease, suggesting quenching of FITC within the lysosome. We also observed an increase in tetramethylrhodamine (TMR)-labeled 70-kD dextran, whose fluorescence is not quenched by low pH (Fig. S2 H). Ataxia
telangiectasia and Rad3-related protein (ATR) is another kinase that is associated with the DNA damage response and has similar and often overlapping roles with ATM (Shiloh, 2003). Inhibition or knockdown of ATR did not increase dextran uptake, suggesting this is specific for ATM (Fig. S2, I–L). This is consistent with our previous report demonstrating that the knockdown of ATM, but not ATR, rescues proliferation defects due to metabolic deficiencies (Aird et al., 2015).

To further confirm that the increase in dextran uptake is due to macropinocytosis, we cotreated cells with EIPA. Treatment of cells with EIPA suppressed the ATM-mediated increase in dextran uptake (Fig. 2, A–D). EIPA in combination with the ATM inhibitor did not increase pChk2 (Fig. S2 M), suggesting that the decrease in macropinocytosis is not the result of increased ATM activity. EIPA alone decreased pChk2, although to varying degrees in the cell lines tested. These data indicate that the signaling downstream of ATM to regulate macropinocytosis is likely not through Chk2, and pChk2 is only a surrogate for confirming the activity of the ATM inhibitors. Macropinosome formation requires Rac1 activity for actin remodeling and membrane ruffling (Fujii et al., 2013), and the inhibition of Rac1 using eHop-016 also decreased dextran uptake (Fig. 2 B). Together, these data indicate that suppression of ATM induces macropinocytosis.

Suppression of macropinocytosis limits survival only in ATM-inhibited cells

We next aimed to determine whether macropinocytosis is required for the survival of ATM-inhibited cells. We treated cells with the ATM inhibitor KU60019 and inhibited macropinocytosis using EIPA. The combination decreased proliferation and increased apoptosis compared with single-treatment controls in multiple cell lines (Fig. 3, A and B; and Fig. S3, A and B). Analysis of proliferation data shows modest synergy (Fig. S3 C). These experiments were performed in replete media, which modestly increases dextran uptake after a chronic 3-d exposure to the ATM inhibitor that is inhibited by EIPA (Fig. S3 D; media conditions detailed in Materials and methods). Modest synergy...
was also observed using nutrient-limiting media (Fig. S3 E). Inhibition of Rac1 using eHop-016 also decreased proliferation in combination with the ATM inhibitor in multiple media (Fig. S3, F and G). The same concentration of EIPA did not affect the proliferation of nonmacropinocytotic normal fibroblasts (Fig. S3 H). In in vivo experiments, the synergy between the ATM inhibitor and EIPA was more pronounced (Fig. 3, C–E). The combination also induced apoptosis as we observed increased cleaved caspase 3 staining by immunohistochemistry (IHC) in the tumors (Fig. 3, F and G). We also validated that KU60019 inhibited ATM by blotting for pChk2 in the tumors (Fig. 3 H and Fig. S3 I). Similar to our in vitro studies, we noted that pChk2 was decreased in the EIPA-alone treated mice. To confirm whether the inhibition of ATM induces macropinocytosis in vivo, mice were injected with fluorescently labeled 70-kD dextran 30 min prior to harvesting the tumor. Consistent with our in vitro data (Fig. 2), KU60019 induced macropinocytosis, which was suppressed by EIPA (Fig. 3, I and J). Together, these data demonstrate that inhibition of macropinocytosis limits proliferation/survival only of cells where ATM is inhibited.

Macropinocytosis induced by ATM inhibition increases BCAA uptake and affects mTORC1 activity

Next, we aimed to determine the metabolic consequences of increased macropinocytosis due to the inhibition of ATM. Previous studies have demonstrated that diverse nutrients including proteins, lipids, glucose, amino acids, and others are taken up by macropinocytosis to promote cancer cell survival under nutrient stress (Commissio et al., 2013; Hodakoski et al., 2019; Kamphorst et al., 2015; Kim et al., 2018; Lee et al., 2019; Palm, 2019; Palm et al., 2017; Recouvrez and Commissio, 2017; Redelman-Sidi et al., 2018; Tejeda-Munoz et al., 2019; Zhang and Commissio, 2019). Thus, we reasoned that metabolites needed to support survival in ATM-inhibited cells would suppress macropinocytosis. Toward this goal, we supplemented cells in basal media with a variety of nutrients. Supplementation with amino acids, but not with glucose, glutamine, or pyruvate, decreased the ATM inhibitor-mediated dextran uptake (Fig. 4 A). While nonessential amino acids (NEAAs) did not affect dextran uptake, supplementation of BCAAs partially but significantly decreased dextran uptake (Fig. 4 B), although we cannot rule out increased uptake via transporters that then suppress macropinocytosis. To better assess whether BCAAs are taken up by macropinocytosis, we used isotope-labeled BCAAs and observed an increase in labeled valine and (iso)leucine in ATM-inhibited cells (Fig. 4 C). Intracellular BCAA abundance was also increased in this condition (Fig. S4 A), supporting the interpretation that the observed increase in labeling is not due to a decrease in the intracellular BCAA pool size (Fig. S4 B). Using publicly available datasets from cell lines (depmap.org), we found protein expression of ATM or pChk2 negatively correlated with the abundance of BCAAs (Fig. 4 D and Fig. S4 C), suggesting that this is a more general phenomenon of ATM low cells. BCAAs can either be catabolized into alpha ketoacids for downstream metabolic processes or directly affect mTORC1 (in the case of leucine/isoleucine) and protein synthesis (Sivanand and Vander Heiden, 2020). While we did not observe marked differences in alpha ketoacids (KIV, KIC or KIV) in ATM-inhibited cells (Fig. S4 D), inhibition of ATM decreased phosphorylation of S6K and 4EBP1 (Fig. 4, E and F), although to a different extent in the cell lines tested. These data suggest a decrease in mTORC1 activity. There was also a positive correlation between phosphorylation of ATM pathway activation and mTORC1 pathway activation in ovarian cancer patient samples from The Cancer Genome Atlas (TCGA; Fig. S4 E). In vitro, supplementation of BCAAs rescued the ATM inhibitor-mediated decrease in mTORC1 activity (Fig. 4 D).
and slightly rescued the decrease in proliferation in combined ATM inhibitor and macropinocytosis inhibitor-treated cells (Fig. S4 F). These data are consistent with previous literature demonstrating that inhibition of mTORC1 activity upregulates macropinocytosis (Dendo et al., 2018; Sung et al., 2015). In contrast, other studies have shown that mTORC1 is activated by macropinocytosis (Meng et al., 2022; Pacitto et al., 2017; Yoshida et al., 2015), or mTORC1 controls the balance between extracellular protein scavenging, catabolism in the lysosome, and protein translation rates (Nofal et al., 2017; Palm et al., 2015). The discrepancy in these observations may be due to media conditions and an acute vs. chronic response. In our studies, mTORC1 was decreased in the acute setting in nutrient-limiting conditions where few extracellular metabolites are available to be consumed. The addition of BCAAs rescued the suppression of mTORC1 activity in this acute setting. It is possible that a more chronic exposure of cells to ATM inhibitors may in fact increase mTORC1 through the enhanced uptake of BCAAs. Furthermore, exactly how ATM inhibition is decreasing mTORC1 activity in these cells remains to be determined. Previous studies have linked ATM signaling upstream of mTORC1 to both positively and negatively regulating its activity (Alexander et al., 2010; Sung et al., 2015).
Smida et al., 2016; Stagni et al., 2015; Tripathi et al., 2013; Viniegra et al., 2005). Similarly, how ATM inhibition promotes Rac1 activation, which is required for actin ruffling to initiate macropinosome formation, and whether this is dependent or independent of mTORC1 was not investigated in this study. Further research is warranted to better delineate this signaling pathway in ovarian cancer cells with inhibited ATM under nutrient-stress conditions.

Finally, we aimed to determine whether BCAA uptake is changed in ATM-inhibited tumors in vivo. To investigate metabolite uptake from the microenvironment, we assessed metabolite abundance in the tumor, interstitial fluid, and ascites fluid, which commonly occurs in ovarian cancer models. Interstitial fluid and ascites fluid can be used to assess microenvironment metabolite abundance. While steady-state abundance of BCAAs in the tumor was not significantly changed (Table S1), BCAAs in the interstitial and ascites fluid were decreased upon treatment with the ATM inhibitor and increased in the combination group (Fig. 4 G, Fig. S4 G, and Table S1), suggesting that these metabolites are consumed by ATM inhibited tumors. Two
important caveats of these data are that the combination-treated tumors are dying, meaning that metabolite abundance may be due to a difference in survival and proliferation rather than a difference in metabolic preference. Additionally, we cannot rule out changes in microenvironmental BCAAs from other sources, such as metabolic changes in nontumor cells. Interestingly, other metabolites were altered in tumors treated with the ATM inhibitor (Fig. S4 H and Table S1), including nucleotides, which is consistent with our previous publication (Aird et al., 2015), and we and others have shown that mTORC1 activity directly promotes nucleotide synthesis (Ben-Sahra et al., 2013, 2016; Buj et al., 2019). Together, these data suggest other mechanisms are at play to promote metabolic adaptation under ATM-inhibited conditions. Future work will be aimed at further investigating these pathways.

In summary, we identified a new mechanism of macropinocytosis induction through the inhibition of ATM, which corresponds to a decrease in mTORC1 activity and an increase in the uptake of BCAAs. This study provides a novel mechanism of metabolism controlled by ATM inhibition and suggests that macropinocytosis represents a metabolic vulnerability that can be targeted in combination with ATM inhibitors, which have recently entered clinical trials (clinicaltrials.gov). Moreover, this pathway may also be a vulnerability of ATM-mutated- or low-expressing tumors. Since Ataxia telangiectasia (A-T) patients with ATM mutations also have metabolic disorders, our data may have implications beyond cancer for controlling metabolism in the context of low or mutated ATM.

Materials and methods

Cell lines and culture conditions

Ovcar8, Ovcar3, and Ovcar10 cells were cultured in RPMI-1640 (Cat# 10-040-CV; Corning) with 5% FBS. 293FT cells were cultured in DMEM (Cat# 10-013-CV; Corning) with 5% FBS. Normal diploid IMR90 (purchased from ATCC) was cultured in low oxygen (2% O2) in DMEM (Cat# 10-017-CV; Corning) with 10% FBS supplemented with l-glutamine, nonessential amino acids, sodium pyruvate, and sodium bicarbonate. Experiments were performed on IMR90 between population doubling #25-35. All cell lines were cultured in MycoZap and were routinely tested for mycoplasma using a highly sensitive PCR-based method (Uphoff and Drexler, 2005). Tumor cell lines were authenticated by genetic analysis or by classification under the guidelines of the American Type Culture Collection (ATCC). 

Media conditions for experiments

The following media conditions were used for experiments, which are indicated in the figure legends: “replete media”: RPMI-1640 (Cat# 10-040-CV; Corning) supplemented with 5% FBS; “low serum media”: RPMI-1640 (Cat# 10-040-CV; Corning) supplemented with 0.1% FBS; “basal media”: Cat# D5030; Sigma-Aldrich without serum; “1% AA media” 1% AA media (99 parts D5030, 1 part complete RPMI-1640 + 5% FBS; final FBS = 0.05% FBS [Jayashankar and Edinger, 2020]).

Glucose uptake by flow cytometry

Cells (10^5/well in 12-well plates) were incubated with 5 μM fluorescent glucose analog 2NBGD (N13195; Thermo Fisher Scientific) in Opti-MEM I Reduced Serum Medium (31985088; Thermo Fisher Scientific) for 2 h. Cells were run on a 10-color FACSCanto flow cytometer (BD Biosciences). Data were analyzed with FlowJo Software.

YSI bioanalyzer analysis

Glucose and glutamine consumption was measured using a YSI 2950 Bioanalyzer (Yellow Springs). Briefly, the same number of cells (10^5/well in 12-well plates) were seeded in complete media. One day later, the media was changed to RPMI-1640+0.1% FBS and the cells were incubated in 10 μM KU60019 (ApexBio) or 1 μM AZD0156 (ApexBio) for 24 h. Media was collected and the number of cells per well was counted to normalize for cell number.

Western blotting

Cell lysates were collected in 1× sample buffer (2% SDS, 10% glycerol, 0.01% bromophenol blue, 62.5 mM Tris, pH 6.8, 0.1M DTT) and boiled (10 min at 95°C). Protein concentration was determined using the Bradford assay. Proteins were resolved using SDS-PAGE gels and transferred to nitrocellulose membranes (Thermo Fisher Scientific; 110 mA for 2 h or overnight at 4°C). Membranes were blocked with 5% nonfat milk or 4% BSA in TBS containing 0.1% Tween-20 (TBS-T) for 1 h at room temperature. Membranes were incubated overnight at 4°C in primary antibodies (Table S2) in 4% BSA/TBS + 0.025% sodium azide. Membranes were washed four times in TBS-T for 5 min at room temperature after which they were incubated with HRP-conjugated secondary antibodies (Cell Signaling) for 1 h at room temperature. After washing four times in TBS-T for 5 min at room temperature, proteins were visualized on a film after incubation with SuperSignal West Pico PLUS Chemiluminescent Substrate (Thermo Fisher Scientific).

Lentiviral packaging and infection

Lentiviral constructs were transfected into 293FT cells using polyethylenimine (PEI). Lentivirus was packaged using the ViraPower Kit (Invitrogen) following the manufacturer’s instructions. Cells were infected overnight with lentivirus targeting the gene of interest or control shGFP and selected with 1 μg/ml puromycin for 3 d. The following shRNAs were used: shATM#1: TRCN0000038658; shATM#2: TRCN0000010299; shATR#1: TRCN0000039615; shATR#2: TRCN0000039616; shSLC2A1a#1: TRCN0000043585; shSLC2A1a#2: TRCN0000043584; shSLC2A4a#1: TRCN0000043628; shSLC2A4a#2: TRCN0000043629; shSLC1A5a#1: TRCN0000043118; shSLC1A5a#2: TRCN0000043119.

RT-qPCR

Total RNA was extracted from cells with Trizol, Dnase-treated, cleaned, and concentrated using Zymo columns (Cat# R1013; Zymo Research) following the manufacturer’s instructions. Optical density values of RNA were measured using NanoDrop One (Thermo Fisher Scientific) to confirm an A260 and A280 ratio above 1.9. Relative expression of target genes (Table S3) was determined using the QuantaSoft 3 Real-Time PCR System (Thermo Fisher Scientific) with clear 96-well plates (Greiner Bio-One). Primers were designed using the Integrated DNA Technologies’ designing software and purchased from Bio-One. Primers were designed using the Integrated DNA Technologies’ designing software and purchased from Bio-One.

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Dextran uptake by flow cytometry
For Dextran-FITC experiments, cells were incubated with 1 or 5 mg/ml dextran-FITC (Cat # 90718-1G; Sigma-Aldrich) in the indicated media conditions. Where indicated, cells were incubated with 10 μM KU60019, 25 μM EIPA, 200 μM BCAAs (mixture of valine [Cat # V0500-1G; Sigma-Aldrich], isoleucine [Cat # I2752-25G; Sigma-Aldrich], and leucine [Cat # L8000-1G; Sigma-Aldrich]), 2.5 μM EHop-016 (Selleck Chemicals), 5 mM glucose, 1 mM pyruvate (Cat # 25-0000-CI; Corning), 2 mM glutamine (Cat # G7513-100 ml; Sigma-Aldrich), 0.2 mM amino acids mixture (NEAAs, glutamine, BCAAs), or 0.1 mM NEAAs (Cat # 25-025-CI; Corning). For TMR-dextran, cells were incubated with 0.1 mg/ml TMR-dextran (Cat # D1818; Invitrogen) for 2 h. After washing once with 1× PBS, cells were incubated for 5 min in 0.1 M NaAc (pH 5.5) to quench dextran-FITC bound to the cell membrane. Cells were then trypsinized and run on a 10-color FACS Canto flow cytometer (BD Biosciences). For Annexin V/7AAD experiments, cells (2 × 104/well in 12-well plates) were treated for 4 d with 2 μM KU60019 and 2 μM EIPA in RPMI + 5% FBS. Cells were stained with 2 × 106 cells/ml Annexin V (R37176; Corning), 2 mM glutamine (Cat # G7513-100 ml; Sigma-Aldrich), 0.2 mM amino acids mixture (NEAAs, glutamine, BCAAs), or 0.1 mM NEAAs (Cat # 25-025-CI; Corning). For TMR-dextran, cells were incubated with 0.1 mg/ml TMR-dextran (Cat # D1818; Invitrogen) for 2 h. After washing once with 1× PBS, cells were incubated for 5 min in 0.1 M NaAc (pH 5.5) to quench dextran-FITC bound to the cell membrane. Cells were then trypsinized and run on a 10-color FACS Canto flow cytometer (BD Biosciences).
Metabolomics

Metabolomic profiling was conducted using ion-pairing reversed-phase liquid chromatography–high resolution mass spectrometry (LC-HRMS) modified from previous methods for polar analytes (Guo et al., 2016) and nucleotides (Kuskovsky et al., 2019). Samples were spiked with a stable isotope mix containing AMP-\(^{13}\)C\(^{10}\),\(^{15}\)N\(^5\), dAMP-\(^{13}\)C\(^{10}\),\(^{15}\)N\(^5\), dATP-\(^{13}\)C\(^{10}\),\(^{15}\)N\(^5\), dATP-\(^{13}\)C\(^{10}\),\(^{15}\)N\(^5\), dTMP-\(^{13}\)C\(^{10}\),\(^{15}\)N\(^5\), dTTP-\(^{13}\)C\(^{10}\),\(^{15}\)N\(^5\), dCMP-\(^{13}\)C\(^{10}\),\(^{15}\)N\(^5\), CTP-\(^{13}\)C\(^{10}\),\(^{15}\)N\(^5\), dCTP-\(^{13}\)C\(^{10}\),\(^{15}\)N\(^5\), \(^{13}\)C\(^{5}\)–sodium pyruvate, \(^{13}\)C\(^{5}\)–lactate, \(^{13}\)C\(^{5}\)–fumaric acid, \(^{13}\)C\(^{5}\)–succinic acid, \(^{13}\)C\(^{6}\)–aspartic acid, \(^{13}\)C\(^{5}\)–citric acid, \(^{13}\)C\(^{5}\)–glucose-6-phosphate, \(^{13}\)C\(^{5}\)–acetoylCoA, \(^{13}\)C\(^{5}\)–D-\(^{15}\)hydroxyglutaric acid, \(^{12}\)C\(^{15}\)N\(^2\)–glutamine from Sigma-Aldrich or Cambridge Isotope Laboratories. 1 ml of Optima LC-MS grade 80:20 methanol/water prechilled to \(-80^\circ\)C was then added to each sample, followed by 30-s vortex mixing, 15-s pulse sonication with a probe tip sonicator, and then the samples were returned to the \(-80^\circ\)C freezer for 30 min. Insoluble debris was precipitated by centrifugation for 10 min, 17,000 \(\times g\) at \(4^\circ\)C. The supernatant was evaporated to dryness under nitrogen, resuspended in 100 \(\mu\)l 5% S-sulfosalicylic acid in water, and 5 \(\mu\)l was injected for analysis. LC-HRMS was conducted on an Ultimate 3000 UHPLC equipped with a refrigerated autosampler (at \(6^\circ\)C) and a column heater (at \(55^\circ\)C) with a HSS C18 column (2.1 \(\times\) 100 mm i.d., 3.5 \(\mu\)m; Waters) used for integration of the peak area of all analytes and NIS-Elements software. H score was determined on blinded samples, where H score = \(\left[1 \times \left(\% \text{ cells 1}\right) + 2 \times \left(\% \text{ cells 2}\right) + 3 \times \left(\% \text{ cells 3}\right)\right]\).

Quantification and statistical analysis

GraphPad Prism version 9.0 was used to perform statistical analysis. One-way ANOVA or unpaired, two-sided t tests were used as appropriate to determine the P values of raw data. Data distribution was assumed to be normal, but this was not formally tested. Longitudinal and cross-sectional analysis of tumor volume were calculated using TumorGrowth tool using default parameters (Enot et al., 2018). P values <0.05 were considered significant.

Online supplemental material

Fig. S1 (complementary to Fig. 1) shows that inhibition of ATM in additional cell lines increases glucose and glutamine consumption, and parental cell lines expressing shRNA against GLUT1, GLUT4, or SLC2A4 have decreased uptake of glucose or glutamine. Fig. S2 (complementary to Fig. 2) shows that inhibition or knockdown of ATM, but not ATR, increases macropinocytosis. Fig. S3 (complementary to Fig. 3) shows that the combination of ATM inhibitor and macropinocytosis inhibitor is synergistic in additional cell lines and different media conditions. Fig. S4 (complementary to Fig. 4) shows that the relative abundance of BCAAs is increased by ATM inhibition and decreased by EIPA in vitro. Fig. S4 also shows the tumor metabolites in different conditions. Table S1 shows the tumor, ascites, and interstitial fluid metabolite data associated with Fig. 4 G; and Fig. S4, G and H. Table S2 is the list of the antibodies used in this study. Table S3 is a list of primers used for this study.

Acknowledgments

This work was supported by grants from the National Institutes of Health (F31CA236372 to E.S. Dahl, F31CA250366 to K.E. Leon, operating in negative mode. The operating conditions were as follows: spray voltage 4000 V; vaporizer temperature 200°C; capillary temperature 350°C; S-lens 60; in-source CID 1.0 eV, and resolution 60,000. The sheath gas (nitrogen) and auxiliary gas (nitrogen) pressures were 45 and 10 (arbitrary units), respectively. Single ion monitoring (SIM) windows were acquired around the [M-H] of each analyte with a 20 m/z window, 4 m/z isolation window offset, 1e6 AG target and 80 ms IT, alternating in a Full MS scan from 70 to 950 m/z with 1e6 AG and 100 ms IT. Data were analyzed in Xcalibur v4.0 and/or TraceFinder v4.1 (Thermo Fisher Scientific) using a 5 ppm window for integration of the peak area of all analytes and internal standards used for normalization. For BCA labeling experiments, cells were incubated for 2 h with 100 \(\mu\)M labeled BCAAs [Cambridge Isotope Laboratories: L-LEUCINE (\(^{13}\)C\(^{6}\), 99%; \(^{15}\)N, 99%), Cat# CNLM-281-H; L-ISOLEUCINE (\(^{13}\)C\(^{6}\), 99%; \(^{15}\)N, 99%), Cat# CNLM-561-H; L-VALINE (\(^{13}\)C\(^{6}\), 99%; \(^{15}\)N, 99%), Cat# CNLM-442-H]. Mass spectrometry methods are described above. Pool size in labeling experiments was calculated as the sum of peak areas of all isotopologs (including \(^{13}\)C and \(^{15}\)N). Isotopolog enrichment was calculated by FluxFix (Trefely et al., 2016). For targeted BCAA quantification in unlabeled conditions, the method was the same, except that samples were spiked with \(^{13}\)C\(^{5}\)–\(^{15}\)N-leucine and \(^{13}\)C\(^{5}\)–\(^{15}\)N-valine before extraction, and analysis was conducted using the ratio of the BCAAs to their labeled internal standards.

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IHC

IHC was conducted on formalin-fixed paraffin-embedded tissues using rabbit anti-cleaved caspase 3 antibody (1:300; Cate 9661; Cell Signaling), EnVision+ Dual Link HRP secondary (Cate K406311-2; Agilent), and the ImmPACT DAB Peroxidase (HRP) Substrate (Cate SK-4105; Vector Laboratories) following the manufacturer’s instructions. Briefly, the tissue was rehydrated by incubating in a series of zylenes/ethanol baths. Antigen retrieval was performed by steaming in citrate buffer (Cate 005000; Thermo Fisher Scientific) for 40 min. Endogenous peroxidase was quenched by incubating in 3% H\(_2\)O\(_2\)/MeOH for 20 min after which slides were washed and blocked in 1% BSA/PBS at room temperature for 30 min. Slides were incubated overnight at 4°C in primary antibody (1:300), washed, and incubated in secondary-HRP for 45 min. DAB was used to develop, and Mayer’s Hematoxylin (Cate MHS16; Sigma-Aldrich) was used to counterstain the tissue. Finally, slides were dehydrated and mounted using Cytoseal. Images were acquired at room temperature using a Nikon Ti-E microscope with a 10×/0.45 objective (Nikon CFI Plan APO Lambda) equipped with a DS-FI3 camera and NIS-Elements software. H score was determined on blinded samples, where H score = \(\left[\right.\times \left(\% \text{ cells 1}\right) + 2 \times \left(\% \text{ cells 2}\right) + 3 \times \left(\% \text{ cells 3}\right)\right]\).

Quantification and statistical analysis

GraphPad Prism version 9.0 was used to perform statistical analysis. One-way ANOVA or unpaired, two-sided t tests were used as appropriate to determine the P values of raw data. Data distribution was assumed to be normal, but this was not formally tested. Longitudinal and cross-sectional analysis of tumor volume were calculated using TumorGrowth tool using default parameters (Enot et al., 2018). P values <0.05 were considered significant.

Online supplemental material

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Figure S1. **Inhibition of ATM increases glucose and glutamine consumption in multiple cell lines; related to** Fig. 1. (A) Ovcar3 and Ovcar10 cells were treated with the ATM inhibitor KU60019 (10 μM) for 24 h in RPMI-1640 + 1% FBS. pChk2 and total Chk2 expression were determined by immunoblotting. Vinculin was used as a loading control. One of three experiments is shown. (B) Ovcar3 cells were treated with the ATM inhibitor KU60019 (10 μM) for 24 h in RPMI-1640 + 1% FBS, and glucose and glutamine consumption was determined. n = 9/group, one of two experiments is shown. Data represent mean ± SD. *P < 0.005; unpaired two-sided t test. (C) Same as B, but for Ovcar10 cells. (D) Glucose uptake in the indicated cells by 2NBDG was determined by flow cytometry after treatment with the ATM inhibitor KU60019 (10 μM) for 24 h in RPMI-1640 + 1% FBS. MFI = median fluorescence intensity. n = 3/group, one of at least two experiments is shown. Data represent mean ± SD. *P < 0.05; unpaired two-sided t test. (E) Parental Ovcar3 cells were infected with lentivirus expressing short hairpin RNAs (shRNAs) targeting SLC2A1 (GLUT1) or SLC2A4 (GLUT4). shGFP was used as a control. Glucose uptake was determined using the fluorescent glucose analog 2NBDG by flow cytometry. n = 6/group, one of two experiments is shown. Data represent mean ± SD. *P < 0.0001 vs. control; one-way ANOVA. (F) Parental Ovcar8 cells were infected with lentivirus expressing shRNAs targeting SLC1A5. shGFP was used as a control. Glutamine uptake was determined. n = 9/group, one of two experiments is shown. Data represent mean ± SEM. *P < 0.0001 vs. control; one-way ANOVA.
Figure S2. Inhibition of ATM, but not ATR, induces macropinocytosis; related to Fig. 2. (A) Ovcar8 cells were treated with the ATM inhibitor KU60019 (10 μM) in combination with EIPA (25 μM) for 24 h in RPMI-1640 + 0.1% FBS. Glucose and glutamine uptake were determined. n = 9/group, one of three experiments is shown. Data represent mean ± SD. *P < 0.005; unpaired two-sided t test. (B) Gating strategy for dextran uptake flow cytometry experiments is shown. (C) Ovcar8 cells were treated with the ATM inhibitor KU60019 (10 μM) for 2 h using the indicated media conditions and dextran uptake was determined by flow cytometry. N = 3/group, one of three experiments is shown. Data represent mean ± SD. *P < 0.01; unpaired two-sided t test. (D) Ovcar8 cells were treated with the ATM inhibitor AZD0156 (1 μM) for 2 h in basal media, and dextran uptake was determined by flow cytometry. n = 3/group, one of three experiments is shown. Data represent mean ± SD. *P < 0.005 vs. control; one-way ANOVA. (E and F) Ovcar8 cells were infected with lentivirus expressing short hairpin RNAs (shRNAs) targeting ATM. shGFP was used as a control. (E) Immunoblot analysis of ATM. Vinculin was used as a loading control. One of five experiments is shown. (F) Dextran uptake in basal media was determined by flow cytometry. n = 3/group, one of five experiments is shown. Data represent mean ± SD. *P < 0.0001 vs. control; one-way ANOVA. (G) Ovcar8 cells were treated with the ATM inhibitor KU60019 (10 μM) for the indicated time points in basal media, and dextran uptake was determined by flow cytometry. Data shown are the ratio of % cells with high dextran uptake in KU60019-treated cells vs. vehicle controls at each time point. n = 3/group, one of three experiments is shown. Data represent mean ± SD. *P < 0.0001 vs. control; one-way ANOVA. (H) Ovcar8 cells were treated with the ATM inhibitor KU60019 (10 μM) for 2 h in basal media, and 70 kD TMR-dextran uptake was determined by flow cytometry. N = 3/group, one of three experiments is shown. Data represent mean ± SD. *P < 0.0001; unpaired two-sided t test. (I–J) Ovcar8 cells were treated with the ATR inhibitor VE822 (1 μM) for 2 h in basal media. (I) Dextran uptake was determined by flow cytometry. n = 3/group, one of three experiments is shown. Data represent mean ± SD. ns = not significant; unpaired two-sided t test. (J) Immunoblot analysis of p-Chk1 and total Chk1. β-actin was used as a loading control. One of three experiments is shown. (K and L) Ovcar8 cells were infected with lentivirus expressing short hairpin RNAs (shRNAs) targeting ATR. shGFP was used as a control. (K) Immunoblot analysis of ATR. Vinculin was used as a loading control. One of three experiments is shown. (L) Dextran uptake in basal media was determined by flow cytometry. n = 3/group, one of three experiments is shown. Data represent mean ± SD. *P < 0.06; ns = not significant; one-way ANOVA. (M) Ovcar8, Ovcar3, and Ovcar10 cells were treated with the ATM inhibitor KU60019 (10 μM) for 2 h in basal media. Immunoblot analysis of p-Chk2 and total Chk2. β-actin was used as a loading control. One of three experiments is shown.
Inhibition of macropinocytosis inhibits cell proliferation and increases cell death in ATM inhibitor-treated cells. Related to Fig. 3. (A) Ovcar8 cells were treated with the ATM inhibitor KU60019 (2 μM) or the macropinocytosis inhibitor EIPA (2 μM) alone and in combination for 3 d in RPMI-1640 + 5% FBS complete media, and dextran uptake was determined at the end of the experiment. n = 3/group, one of two experiments is shown. Data represent mean ± SD. *P < 0.05; one-way ANOVA. (B and C) Ovcar3 (B) or Ovcar10 (C) cells were treated with the ATM inhibitor KU60019 (2 μM) or the macropinocytosis inhibitor EIPA (2 μM) alone and in combination for 3 d in RPMI-1640 + 5% FBS complete media. Proliferation (left panel) was assessed by crystal violet staining. Apoptosis (right panel) was assessed by Annexin V/7AAD staining. n = 3/group, one of three experiments is shown. Data represent mean ± SD. *P < 0.01; one-way ANOVA. (D) Synergy analysis using Combenefit software using the LOEWE model. (E) Ovcar8 cells were treated with the ATM inhibitor KU60019 (2 μM) or the macropinocytosis inhibitor EIPA (1.25 μM) alone and in combination for 3 d in RPMI-1640 + 0.1% FBS complete media. n = 3/group, one of four experiments is shown. Data represent mean ± SD. *P < 0.005; one-way ANOVA. (F) Ovcar8 cells were treated with the ATM inhibitor KU60019 (2 μM) or the Rac1 inhibitor eHop-016 (1.75 μM) alone and in combination for 3 d in RPMI-1640 + 5% FBS complete media. Proliferation was assessed by crystal violet staining. One of four experiments is shown. Data represent mean ± SD. *P < 0.001; one-way ANOVA. (G) Ovcar8 cells were treated with the ATM inhibitor KU60019 (2 μM) or the Rac1 inhibitor eHop-016 (1.4 μM) alone and in combination for 2 d in RPMI-1640 + 0.1% FBS complete media. Proliferation was assessed by crystal violet staining. One of two experiments is shown. Data represent mean ± SD. *P < 0.0001; one-way ANOVA. (H) IMR90 fibroblasts (non-macropinocytotic) were treated with the macropinocytosis inhibitor EIPA (2 μM) for 3 d. Proliferation was assessed by crystal violet staining. Data represent mean ± SD. ns = not significant. Unpaired two-sided t test. One of two experiments is shown. (I) pChk2 and total Chk2 immunoblot analysis in all of the tumors. β-Actin was used as a loading control.
Provided online are three supplemental tables. Table S1 shows tumor metabolites. Table S2 shows antibodies used in the current studies. Table S3 shows RT-qPCR primers.