Breast cancer is the most common cancer among American women and a major cause of mortality. To identify metabolic pathways as potential targets to treat metastatic breast cancer, we performed metabolomics profiling on the breast cancer cell line MDA-MB-231 and its tissue-tropic metastatic subclones. Here, we report that these subclones with increased metastatic potential display an altered metabolic profile compared with the parental population. In particular, the mitochondrial serine and one-carbon (1C) unit pathway is upregulated in metastatic subclones. Mechanistically, the mitochondrial serine and 1C unit pathway drives the faster proliferation of subclones through enhanced de novo purine biosynthesis. Inhibition of the first rate-limiting enzyme of the mitochondrial serine and 1C unit pathway, serine hydroxymethyltransferase (SHMT2), potently suppresses proliferation of metastatic subclones in culture and impairs growth of lung metastatic subclones at both primary and metastatic sites in mice. Some human breast cancers exhibit a significant association between the expression of genes in the mitochondrial serine and 1C unit pathway with disease outcome and higher expression of SHMT2 in metastatic tumor tissue compared with primary tumors. In addition to breast cancer, a few other cancer types, such as adrenocortical carcinoma and kidney chromophobe cell carcinoma, also display increased SHMT2 expression during disease progression. Together, these results suggest that mitochondrial serine and 1C unit metabolism plays an important role in promoting cancer progression, particularly in late-stage cancer.

Implications: This study identifies mitochondrial serine and 1C unit metabolism as an important pathway during the progression of a subset of human breast cancers.

Introduction

The majority of breast cancer patients die from metastatic disease. The process of cancer metastasis involves local invasion into surrounding tissue, dissemination into the bloodstream, extravasation, and eventual colonization of a new tissue. Following a period of dormancy, small numbers of micrometastases eventually proliferate into large macrometastases, or secondary tumors.

Previous studies have illuminated several themes of metabolic reprogramming that occur during metastasis (1–8). However, the majority of these reported site-specific metabolic features of metastatic cancer cells. We reason that breast cancer cells that leave the primary tumor and successfully establish new lesions at distal sites would encounter similar metabolic stresses during metastasis. By performing comparative metabolomics on the MDA-MB-231 human breast cancer cell line and its tissue-tropic metastatic subclones, we uncovered that the catabolism of the nonessential amino acid serine through the mitochondrial one-carbon (1C) unit pathway is an important driver of proliferation in a subset of metastatic breast cancers that closely resembles the molecular features of MDA-MB-231 cells. Emerging evidence shows that the nonessential amino acid serine is essential for cancer cell survival and proliferation. The genomic regions containing PHGDH are amplified in breast cancer and melanoma, diverting 3PG to serine synthesis (9, 10). We also reported that PHGDH is upregulated upon amino acid starvation by the transcription factor ATF4 (11). On one hand, serine serves as a precursor for the synthesis of protein, lipids, nucleotides, and other amino acids, which are necessary for cell division and growth. On the other hand, serine catabolism through the mitochondrial 1C unit pathway is critical for maintaining cellular redox control under stress conditions (12, 13). In mitochondria, serine catabolism is initiated by serine hydroxymethyltransferase 2 (SHMT2). SHMT2 catalyzes a reversible reaction converting serine to glycine, with concurrent generation of the 1C unit donor methylene-THF, which is further oxidized by the downstream enzymes MTHFD2 and MTHFD1L to produce NAD(P)H and formate. Subsequent export of formate from the mitochondria can then be reassimilated into the cytosolic folate pool to support anabolic reactions. All three mitochondrial serine and 1C unit pathway enzymes (SHMT2, MTHFD2, and MTHFD1L) are upregulated in breast tumor samples compared with normal tissues (13, 14). However, due to a lack of functional
investigations targeting this pathway in \textit{in vitro} and \textit{in vivo} breast cancer models, it remains unclear whether the mitochondrial 1C unit pathway represents a good target for treating metastatic breast cancer.

In this study, we report that enzymes in the mitochondrial serine and 1C unit pathway are even further upregulated specifically in subclones of the aggressive breast cancer cell line MDA-MB-231 that have been selected \textit{in vivo} for the ability to preferentially metastasize to specific organs. We demonstrate that SHMT2 inhibition suppresses proliferation more strongly in these highly metastatic subclones compared with the parental population \textit{in vitro}. Knockdown of SHMT2 also impairs breast cancer growth \textit{in vivo} at both the primary and metastatic sites. In addition, we find that the expression of mitochondrial 1C unit pathway enzymes is significantly associated with poor disease outcome in a subset of human breast cancer patients, potentiating its role as a therapeutic target or biomarker in advanced cancer. Finally, SHMT2 expression increases in breast invasive carcinoma, adenocortical carcinoma, chromophobe renal cell carcinoma, and papillary renal cell carcinoma during tumor progression, particularly in late-stage tumors, suggesting that inhibitors targeting SHMT2 may hold promise for treating these late-stage cancers when other therapeutic options become limited.

\section*{Materials and Methods}

\subsection*{Cell lines}

All of the paired parental and metastatic subclones were generated in Dr. Joan Massagué’s laboratory (Memorial Sloan Kettering Cancer Center; refs. 15–17). Cells were cultured in DMEM/F12 with 10% fetal bovine serum (Sigma) with 1% penicillin/streptomycin. All cell lines were tested every 3 to 6 months and found negative for Mycoplasma (MycoAlert Mycoplasma Detection Kit; Lonza). These cell lines were not authenticated by the authors. All cell lines used in this study were purchased from the American Type Culture Collection (ATCC) and are intended for research only. After each 4 weeks, surviving mice were sacrificed and lungs snap frozen in liquid N$_2$ prior to homogenization in TRIzol for RNA extraction.

\subsection*{Metabolite profiling and mass spectrometry}

For total metabolite analysis, parental and metastatic cell lines were seeded in 60-mm culture dishes in DMEM/F12 supplemented with 10% dialyzed fetal bovine serum. Media were refreshed 2 hours prior to harvesting by washing 3× with PBS before quenching with 800 mL of –80°C 80:20 methanol:water. Extracts were spun down, supernatants collected, dried, and resuspended in water before LC-MS analysis. Samples were analyzed by reversed-phase ion-pairing chromatography coupled with negative-mode electrospray-ionization high-resolution MS on a stand-alone ThermoElectron Exactive orbitrap mass spectrometer (18). Peak picking and quantification were conducted using MAVEN analysis software. Heat map was generated in R. Multiple testing correction and q-value generation were performed in PRISM software (GraphPad).

For [2,3,3-${}^2$H]serine labeling experiments, parental and metastatic cells were cultured in RPMI medium lacking glucose, serine, and glycine (TEKnova) supplemented with 2 g/L glucose and 0.03 g/L [2,3,3-$^2$H]serine (Cambridge Isotope Laboratories) for up to 24 hours before harvesting. Cells were washed twice with ice-cold PBS prior to extraction with 400 μL of 80:20 acetonitrile:water over ice for 15 minutes. Cells were scraped off plates to be collected with supernatants, sonicated for 30 seconds, then spun down at 1.5 × 10⁴ RPM for 10 minutes. Supernatant (200 μL) was taken out for LC-MS/MS analysis immediately. Quantitative LC-ESI-MS/MS analysis of [2,3,3-$^2$H]serine-labeled cell extracts was performed using an Agilent 1290 UHPLC system equipped with an Agilent 6545 Q-TOF mass spectrometer. A hydrophilic interaction chromatography method (HILIC) with a BEH amide column (100 × 2.1 mm i.d., 1.7 μm; Waters) was used for compound separation at 35°C with a flow rate of 0.3 mL/minute. The mobile phase A consisted of 25 mM ammonium acetate and 25 mM ammonium hydroxide in water and mobile phase B was acetonitrile. The gradient elution was 0–1 minute, 85% B; 1–12 minutes, 85% B–65% B; 12–12.2 minutes, 65% B–40% B; 12.2–15 minutes, 40% B. After the gradient, the column was reequilibrated at 85% B for 5 minutes. The overall runtime was 20 minutes, and the injection volume was 5 μL. Agilent Q-TOF was operated in negative mode, and the relevant parameters were as listed: ion spray voltage, 3,500 V; nozzle voltage,
Results

Metastatic breast cancer cells exhibit altered metabolic profiles

To identify common metabolic pathways reprogrammed in metastatic breast cancer cells during cancer progression, we performed metabolomic profiling of the human triple-negative breast cancer cell line MDA-MB-231 and its metastatic subpopulations (Fig. 1A and B). This cell line was derived from the pleural effusion of a patient with widespread metastatic disease years after primary tumor removal (25), and the subclones of this cell line with higher metastasis rate and preference to the bone, lung, or brain were previously isolated by in vivo selection (refs. 15–17; 831-BrM: brain metastasis; 1833-BoM: bone metastasis; 4175-LM: lung metastasis).

At the time of initial metabolomics comparison, the lung metastatic subclone 4175-LM did not recover well in culture, so we profiled the 831-BrM and 1833-BoM metastatic subclones along with the parental population. We observed multiple metabolites involved in a plethora of metabolic pathways that were differentially enriched or depleted in the metastatic 831-BrM and 1833-BoM subclones compared with the parental population of MDA-MB-231 (231-Parental) cells (Fig. 1B). Following correction for false discovery rate, the levels of 24 metabolites were significantly altered in both 831-BrM and 1833-BoM cells compared with 231-Parental cells (Supplementary Table S2). Metabolites significantly enriched in metastatic subclones included the glycolytic intermediate dihydroxyacetone-phosphate (which is reversibly isomerized to glyceraldehyde-3-phosphate), the tricarboxylic acid (TCA) cycle intermediate succinate, amino acids such as proline and asparagine, and the pentose-phosphate pathway product 5-phosphoribosyl-1-pyrophosphate. These observations are consistent with prior observations of perturbations in lower glycolysis and the TCA cycle observed in other cell line models (notably murine 4T1 cells), suggesting common metabolic developments during metastasis of breast cancers in both mice and humans (1–3, 5, 6). Additionally, enrichment of asparagine has been reported to promote metastatic breast cancer cell phenotypes by epithelial-to-mesenchymal transition (8). Nonetheless, the most significantly depleted class of metabolites in 831-BrM and 1833-BoM cells compared with 231-Parental cells was free purine nucleotides, suggesting alterations in purine metabolism in metastatic cells (Fig. 1B).

c-Myc is important for breast cancer cell proliferation

We wondered whether reduced levels of purines reflected decreased synthesis or higher consumption in the metastatic subclones. Because it was previously reported that the oncopgenic transcription factor c-Myc induces the expression of nucleotide biosynthesis genes and that c-Myc amplification and overexpression is a common event in triple-negative breast cancer (26–28), we wondered if the relative differences in purine abundance could be explained by altered c-Myc protein levels in our cell line system. Indeed, 831-BrM, 1833-BoM, and 4175-LM cells overexpressed c-Myc compared with 231-Parental cells (Fig. 2A). Because sufficiency of free nucleotides can act as an important checkpoint for cell division (29), we then compared the proliferation rates of parental and metastatic subclones. Accordingly, 831-BrM, 1833-BoM, and 4175-LM cells proliferated faster than 231-Parental cells in vitro (Fig. 2B), suggesting that the higher consumption rate is the cause of lower purine levels in the metastatic subclones.

Because the role of c-Myc in metastasis is still unclear, with evidence suggesting it plays both prometastatic and antimetastatic functions in breast cancer depending on the genetic context (30, 31), we tested the sensitivity of parental and metastatic subclones to c-Myc inhibition. Small hairpin RNA (shRNA)–mediated knockdown of c-Myc reduced...
Figure 1.
Metastatic breast cancer subclones display an altered metabolic profile. A, Schematic of targeted metabolomics workflow. Brain (831-BrM), bone (1833-BoM), and lung (4175-LM) metastatic subclones from tissue-tropic subpopulations were generated following i.v. injection of a parental population of MDA-MB-231 (231-Parental) cells into the tail vein or heart. Stable cell lines were passaged in culture prior to metabolite extraction for LC-MS/MS. B, LC-MS profile of the 231-Parental, 831-BrM, and 1833-BoM cell lines. Cell lines were plated in biological triplicates prior to metabolite extraction. Signals were normalized to the mean signal of each metabolite across all samples, log2 transformed, and clustered.
cell proliferation in all four cell lines, although the degree of inhibition was stronger in 831-BrM and 1833-BoM cells (Fig. 2C; Supplementary Fig. S1). Parental cells expressing a nontargeting shRNA showed elevated c-Myc expression, possibly due to puromycin selection. These data suggest that c-Myc is an important mediator of cell proliferation, and c-Myc overexpression provided a proliferative advantage at least in brain and bone-metastatic subclones.

Identification of serine and 1C unit pathway elevation in metastatic subclones

The products of several metabolic pathways feed into nucleotide synthesis, including ribulose-5-phosphate from the pentose-phosphate pathway, and 1C units and glycine from the serine and 1C unit pathway. It is also known that c-Myc can promote the expression of serine and glycine metabolism genes in cancer cells (32, 33). We performed expression analyses of the metastatic subclones and found elevated levels of the key mitochondrial enzymes SHMT2, methylenetetrahydrofolate dehydrogenase 2 (MTHFD2), and methylenetetrahydrofolate dehydrogenase 1-like (MTHFD1L), in contrast to the downregulated expression of the cytosolic isoenzyme serine hydroxymethyltransferase 1 (SHMT1; Fig. 3A–C). Consistent with previous reports in other cell types, knockdown of c-Myc in parental and metastatic breast cancer subclones diminished MTHFD2 and MTHFD1L protein expression, suggesting these enzymes are c-Myc regulated (Supplementary Fig. S1). SHMT2 expression did not reduce upon c-Myc knockdown, suggesting that SHMT2 expression was regulated by other transcription factors. To determine whether c-Myc and mitochondrial 1C unit pathway enzyme overexpression was a common co-occurrence in other cancer metastasis models, we checked protein expression levels in the parental and metastatic subpopulations of other human cell line systems derived from lung adenocarcinoma or ER+ breast carcinoma patients (34, 35). There was a clear correlation of SHMT2, MTHFD2, and MTHFD1L expression with c-Myc expression among all the cell lines tested. The brain-metastatic subclones of lung adenocarcinoma cell lines PC9 and H2030 had increased MTHFD2 expression, though we could not find another system that also displayed overexpression of c-Myc and all the three mitochondrial 1C unit pathway enzymes in metastatic subclones relative to their

Figure 2.
c-Myc drives proliferation in metastatic breast cancer cell subclones. A, IB for c-Myc from whole-cell extracts of parental and metastatic subclones. B, Proliferation of parental cells and metastatic subclones over 3 days (mean ± SD, n = 3). C, 3-day proliferation of 231-Parental, 831-BrM, 1833-BoM, and 4175-LM cells expressing either a nontargeting (shNT) or c-Myc targeting (shMyc) vectors (mean ± SD, n = 3).
The mitochondrial serine and 1C unit pathway is upregulated in metastatic breast cancer subclones. A, Schematic of the cytosolic and mitochondrial serine and 1C unit pathway. B, qPCR for serine and 1C unit pathway genes (mean ± SD; n = 3; *, P < 0.05; **, P < 0.01; †††, P < 0.001; ††††, P < 0.0001 by two-tailed Student t test, compared with expression in parental cells). C, IB for serine and 1C unit pathway enzymes from whole-cell extracts of parental cells and metastatic subclones. D, Schematic diagram of incorporation of D from [2,3,3-2H]serine onto glycine, 1C units, and purines. E, SHMT flux estimated by relative abundance of labeled glycine from serine (mean ± SD; n = 3; *, P < 0.05; ††, P < 0.01 by two-tailed Student t test). F, Fractional labeling of [2,3,3-2H]serine onto GTP and ATP (mean ± SD; n = 3; *, P < 0.05; ††, P < 0.01; †††, P < 0.001 by two-tailed Student t test).
Metastatic subclones display increased mitochondrial serine and 1C unit pathway activity

We next asked if higher expression of mitochondrial serine and 1C unit pathway enzymes might indeed reflect higher pathway activity. Serine can be catabolized in both the mitochondrial and cytosolic branch of the 1C unit pathway. Because cancer cells predominately express the mitochondrial serine catabolic enzymes over the cytosolic enzymes, serine is generally catabolized in the mitochondria in cancer cells (13, 14, 36). Serine hydroxymethyltransferase 2 (SHMT2) initiates this reaction by converting serine to glycine while donating a carbon group to tetrahydrofolate (THF) to generate methylene-THF. Subsequent oxidation of methylene-THF by MTHFD2 and MTHFD1L generates NAD(P)H and formate. Formate can cross the mitochondrial membrane to provide 1C units for anabolic reactions such as nucleotide synthesis (37).

We hypothesized that the reason metastatic cells upregulate the serine and 1C unit pathway is to enhance nucleotide synthesis to fuel cell proliferation. Indeed, most cancer cells have been reported to utilize serine as the predominant source of 1C units for biosynthesis (38). We performed [2,3,3-2H]serine tracing to examine 1C unit pathway flux to glycine and purine nucleotides. In cells grown in media containing [2,3,3-2H]serine, the cytosolic pathway generates methylene-THF (me-THF) mass heavy by 2 (M+2) and 10-formyl-THF mass heavy by 1 (M+1), whereas 10-formyl-THF derived from mitochondrial formate exchange to the cytosol is strictly M+1. [2,3,3-2H]serine labeling onto the metabolites glycine and purine nucleotides produced from the mitochondrial pathway thereby produces glycine M+1 and purines either M+1 or M+2 (Fig. 3D). Time-course experiments were performed in 4175-LM cells to determine the optimal steady-state labeling conditions for glycine and ATP from serine: 2 hours and 24 hours, respectively (Supplementary Fig. S3). We observed higher SHMT flux in metastatic subclones, as the relative abundance of M+1 glycine was approximately 1.5-fold higher in 4175-LM cells compared with 231-Parental cells, indicating that higher purine turnover in metastatic cells was fueled by higher SHMT flux (Fig. 3E). Importantly, although robust fractions of ATP and GTP were labeled in parental cells, the metastatic subclones displayed even higher labeling fractions from serine (Fig. 3F). These results demonstrate that upregulation of serine catabolism through the mitochondrial 1C unit pathway promotes de novo purine synthesis in metastatic breast cancer cells.

Serine catabolism is necessary for metastatic cancer cell proliferation in vitro

To address the extent to which mitochondrial serine catabolism is necessary for cell proliferation, 231-Parental, 831-BrM, 1833-BoM, and 4175-LM cells were infected with lentivirus expressing shRNAs against SHMT2 (shSHMT2) or a nontargeting control (shNT). Intriguingly, knockdown of SHMT2 protein expression with two different shRNAs drastically suppressed proliferation of the metastatic subclones significantly, with a reduced effect in 231-Parental cells (Fig. 4A and B). In contrast, knockdown of the downstream enzyme of the mitochondrial serine and 1C unit pathway, MTHFD2, suppressed proliferation to a lesser extent (Supplementary Fig. S4A and S4B). To evaluate the therapeutic potential of targeting 1C unit metabolism to block metastatic growth, we treated cells with a small-molecule inhibitor of SHMT called SHIN1 (39). In vitro, metastatic subclones were sensitive to SHIN1 with an EC50 in the 100 to 500 nmol/L range (Supplementary Fig. S5). There was no obvious enhancement of SHIN1 sensitivity in 831-BrM, 1833-BoM, and 4175-LM cells compared with 231-Parental cells, possibly because SHIN1 inhibits both SHMT2 and SHMT1 (Fig. 4C). Importantly, inhibition of cell proliferation in the presence of SHIN1 could be rescued by the supplementation of formate (2 mmol/L), a source of cellular 1C units (Fig. 4C). These results indicate that the major role of elevated mitochondrial serine catabolism is to generate 1C units for cytosolic purine biosynthesis in the metastatic subclones. Thus, targeting SHMT activity may be a promising way to restrict nucleotide availability to block metastatic breast cancer cell proliferation.

SHMT2 knockdown impairs primary and metastatic growth in vivo

We then interrogated the effect of reducing mitochondrial 1C unit pathway activity in two different models of cancer growth in vivo. 4175-LM cells were chosen due to the relative ease of monitoring, measuring, and collecting tissue from lung metastasis compared with brain and bone metastasis. For the first model, we monitored breast cancer growth at the primary tumor site. SHMT2 knockdown significantly impaired the growth of 4175-LM cells in the mammary fat pads of immunodeficient mice (Fig. 4D; Supplementary Fig. S6). For the second model, we induced breast cancer metastasis to the lung by intravenous tail-vein injection. Because 4175-LM cells express firefly luciferase (16), we tracked tumor growth in the lung by bioluminescence imaging (BLI). Both BLI and quantification of human GAPDH (hGAPDH) expression from resected mouse lungs revealed a roughly 2-fold reduction of lung tumor burden in mice injected with shSHMT2 cells compared with shNT cells (Fig. 4E and F; Supplementary Fig. S7A). Although on average, shSHMT2 tumors had reduced human SHMT2 (hSHMT2) expression compared with shNT tumors, some shSHMT2 tumors appeared to have reacquired hSHMT2 expression (Supplementary Fig. S7B and S7C). These data suggest that SHMT2 is necessary for metastatic growth in vivo.

Mitochondrial serine and 1C unit pathway genes are associated with more aggressive metastatic disease in some human breast cancer patients

To further explore the relevancy of mitochondrial 1C unit metabolism in human breast cancer metastasis, we examined the expression of SHMT1, SHMT2, MTHFD2, and MTHFD1L in the METABRIC data set of human breast cancer patients (21). We retrospectively inferred metastatic recurrence in patients by examining the frequency of DSS up to 20 years. Patients were separated into two groups based on the maxstat algorithm (see Materials and Methods). Patients with high SHMT2 expression were significantly more likely to succumb to metastatic recurrent disease, whereas patients with high expression of the cytosolic isozyme SHMT1 were significantly protected from metastatic relapse (Fig. 5A; Supplementary Fig. S8). Using three different breast cancer subtype clustering analyses based on gene expression (PAM50, IC10, and SCMOD2), we classified the MDA-MB-231 cell line as basal, IC4 (copy-number flat), and ER “Her2−” (20, 21). We have previously described IC4 as consisting of a mixture of ER− tumors with lymphocytic infiltration and ER+ tumors with abundant stroma. Accordingly, further analysis of the IC4
patient subgroup following adjustment for covariates of age, grade, size, number of lymph nodes, ER, PR, and Her2 status revealed a significant association of MTHFD1, MTHFD1L, MTHFD2, and SHMT2 expression with worse survival and SHMT1 expression with better survival (Fig. 5B). Finally, we stained a tissue microarray panel of human breast invasive ductal carcinoma and matched lymph node

Figure 4.
Metastatic subclones are particularly sensitive to SHMT2 inhibition. A, 3-day proliferation of 231-Parental, 831-BrM, 1833-BoM, and 4175-LM cells expressing either a nontargeting (shNT) or SHMT2 targeting (shSHMT2) vectors. Relative proliferation was calculated relative to average proliferation of shNT cells (mean ± SD, n = 3). B, IB for SHMT2 in parental and metastatic subclones. C, 3-day proliferation of parental and metastatic cells with 2 μmol/L SHIN1 in RPMI with or without 2 mmol/L formate and dialyzed FBS (mean ± SD; n = 3; ***, P < 0.001; ****, P < 0.0001 by two-tailed Student t test). Counts were normalized to the proliferation of 231-Parental cells in media without SHIN1 and formate treatment. D, Growth of 4175-LM shNT and shSHMT2 tumors in the mammary fat pad of nude mice (mean ± SEM; n = 8; **, P < 0.01 by two-tailed Student t test). E, Quantification of luminescence signal in the lungs of mice 3 weeks after injection of either 4175-LM shNT or shSHMT2 cells (mean ± SEM; ***, P < 0.01 by two-tailed Student t test, shNT; n = 8 shSHMT2; n = 7). F, qPCR analysis of hGAPDH expression in the lungs of mice 4 weeks after injection of either 4175-LM shNT or shSHMT2 cells (mean ± SEM; *, P < 0.05 by two-tailed Student t test, shNT; n = 6 shSHMT2; n = 7).
metastases and found significantly higher expression of SHMT2 in metastatic cancer cells compared with the primary tumors (Fig. 5C and D). Together, these data suggest that SHMT2 and other mitochondrial 1C unit pathway enzymes may be used as prognostic markers that indicate worse patient outcome, whereas cytosolic SHMT1 expression may indicate a better survival rate in the IC4 patient subgroup.

Relevance of SHMT2 expression in the progression and aggressiveness of other cancer types

To evaluate the contribution of mitochondrial 1C unit metabolism to the progression of other cancer types, we queried SHMT2 expression in TCGA data sets through the UALCAN portal (24). In addition to breast invasive carcinoma (BRCA), we identified adrenocortical carcinoma (ACC), head and neck squamous cell carcinoma (HNSC),

Figure 5.
Mitochondrial serine and 1C unit pathway enzyme expression correlates with poor survival in human breast cancer. A, Kaplan–Meier plot for SHMT1 (left) and SHMT2 (right) expression associated with DSS in the human IC4 patient subgroup (METABRIC). B, Forest plot for the hazard of individual 1C unit pathway genes adjusted for covariates (age, grade, size, number of lymph nodes, ER, PR, and Her2 status) in the IC4 subgroup (n = 343). C, Representative SHMT2 staining (at 40×) of human breast invasive ductal carcinoma and matched metastatic carcinoma tissue samples (LN = lymph node). D, Quantification of SHMT2 intensity by IHC in metastatic lesions compared with primary tumors (mean ± SD; n = 33 per group; *, P < 0.05 by two-tailed Student t test).
kidney chromophobe cell carcinoma (KICH), and kidney renal papillary cell carcinoma (KIRP) as cancer types in which SHMT2 expression progressively increased as a function of stage (Fig. 6). Notably, gain of SHMT2 expression in BRCA and HNSC tended to occur early on in cancer progression, whereas in KICH, SHMT2 upregulation may occur only during the very late stage. A few cancer types such as mesothelioma (MESO) and ovarian serous cystadenocarcinoma (OV) showed the opposite trend: a progressive loss of SHMT2 expression with increasing cancer stage (Supplementary Fig. S9). Collectively, these data present the possibility that there exist additional cancer types in which mitochondrial 1C unit metabolism promotes progression and aggressiveness.

Discussion

For breast cancer, common metastatic sites include the brain, bone, liver, and lung. At the cellular level, the original heterogeneous population of cancer cells from the primary tumor undergoes a selection process whereby those clones with alterations (carrying both genetic lesions and epigenetic modifications) favoring fitness and plasticity are enriched. These adaptations, in turn, equip cells with the ability to withstand standard treatments such as chemotherapy and radiotherapy, ultimately leading to cancer progression and metastatic recurrence (40). Although many previous studies have elucidated a role for molecular processes such as epithelial-to-mesenchymal transition and invasion and migration of cancer cells, our understanding of how
metabolic pathway alterations shape metastatic growth is still limited. It is important to note that the MDA-MB-231 cells we studied were isolated from a pleural population that already metastasizes well in vivo. Our metabolomics profiling of the even more highly metastatic triple-negative breast cancer subclones suggested alterations in both glycolysis and the TCA cycle during the late stages of cancer progression, consistent with findings from other groups of heightened mitochondrial metabolism in metastatic cells (2, 3, 5, 6). We further discovered elevated catabolism of serine in the mitochondria of our metastatic subclones. A previous study in isogenic murine 4T1 breast cancer cell lines found that transformed cells showed higher levels of nucleotides than nontransformed cells, and that "more metastatic" lines had even more nucleotides than "less metastatic" ones (1). In contrast, we found lower levels of free purines in metastatic variants of human MDA-MB-231 cell lines compared with the parental population (Fig. 1B). This discrepancy may be attributed to different oncogenic contexts in 4T1 cells versus MDA-MB-231 cells or inherent differences in purine metabolism between murine and human cells. Due to the difficulty of obtaining pure metastatic tumor tissue from in vivo studies, the metabolomic analysis was performed using established cell lines in vitro. Micro-environmental factors from metastatic niche, such as hypoxia and nutrient starvation, also regulate cancer cell metabolism. Because mitochondrial 1C unit metabolism can utilize both NAD+ and NADP+, cancer cells with upregulation of mitochondrial 1C unit metabolism may gain metabolic flexibility to sustain proliferation under stress conditions. When cells engage active respiration, the mitochondrial 1C unit pathway can utilize NAD+ to generate 1C units; under hypoxia or starvation conditions, when the NAD+/NADH ratio decreases, elevated mitochondrial ROS leads to an increased NADP+/NADPH ratio, which can also drive the 1C unit pathway and purine synthesis. Further investigations comparing the metabolic profile changes under these stress conditions may provide more insight into potential links between metabolic stresses and the evolution of metastatic cancer cells.

The role of serine in cancer growth has drawn increasing interest over the years ever since the identification of PHGDH amplifications in melanoma and breast cancer (9, 10). A variety of mechanisms have been proposed to explain why increased serine synthesis and serine catabolism could promote tumorigenesis, including rerouting glucose carbon flux, maintenance of compartment-specific NAD(P)H/NAD(P) (P)H ratios, and the control of metabolites such as acetyl-coA, α-ketoglutarate, or 2-hydroxyglutarate (12, 41, 42). Moreover, a previous study had implicated SHMT2 and a neutral amino acid importer of serine and glycine (ASCT2) as prognostic biomarkers for human breast cancers, with hyperactive c-Myc enriched particularly in the IC4 subset of human breast cancer cell populations selected for high metastatic activity in mice. As one of the key oncogenic transcription factors, there is increasing evidence that c-Myc plays multiple roles during the metastatic process. c-Myc supports serine/glycine metabolism at the transcriptional level in human breast cancer cells and demonstrated its necessity for the invasive growth of brain metastases (45). Our study highlights the role of c-Myc in enhancing 1C unit pathway activity and proliferation, which is also important for metastatic growth. Because SHMT2 expression was not reduced by c-Myc shRNA, it is likely that other tumor-promoting factors, such as ATF4 and NRF2, also play important roles in late-stage cancer progression by modulating 1C unit metabolism. Intriguingly, a recent report showed that TGFβ signaling induces the expression of SHMT2 (46). Given the critical role of TGFβ in promoting metastasis (47, 48), it may be interesting to further investigate whether serine and 1C unit pathway metabolic reprogramming is controlled by TGFβ signaling in metastatic subpopulations of human breast cancer cells.

**Disclosure of Potential Conflicts of Interest**

J. Massagué is a scientific advisor for Scholar Rock, Inc., has received honoraria from speakers bureau of Skirball Institute, and is an unpaid consultant/advisory board member on the editorial boards of Cancer Discovery, Cell, EMBO J, Genes Dev and J. Cell Biol. J.D. Rabinowitz is founder/SAB of Raze Therapeutics and has ownership interest (including patents) in Princeton University. C.B. Thompson is a scientific advisory board member for Agios and Merck, is on the board of directors of Charles River Laboratories, and has ownership interest (including patents) in Agios, Merck, and Charles River Laboratories. No potential conflicts of interest were disclosed by the other authors.

**Authors’ Contributions**

Conception and design: A.M. Li, E.B. Rankin, C.B. Thompson, J. Ye

Development of methodology: A.M. Li, Y. Li, Y. Xiao, L. Liu, J.D. Rabinowitz

and lung. In addition, we found that in the IC4 subset of human breast cancer patients, the expression of mitochondrial 1C unit enzymes is positively associated with more aggressive disease. Thus, interrogating the expression status of mitochondrial 1C unit enzymes through transcriptional or proteomic methods holds prognostic value in the metastatic setting, and warrants the need for further development of drugs that selectively inhibit serine catabolism for treating the metastasis of triple-negative breast cancer.

What causes the upregulation of mitochondrial serine catabolic flux in highly metastatic cancer cells? We provide evidence that a crucial oncogenic event promotes the ability of metastatic breast cancer subclones to catabolize serine faster than parental cells: c-Myc activation. c-Myc overexpression is known to be associated with up to 40% of breast cancers, with hyperactive c-Myc enriched particularly in the basal-like subtype (27, 44). These observations are consistent with our findings of the MDA-MB-231 cell line as basal-like and its metastatic subclones expressing even higher levels of c-Myc than the parental population (Fig. 2A). We found that c-Myc was required for the maintenance of the mitochondrial serine and 1C unit pathway genes MTHFD2 and MTHFD1L consistent with previous reports that c-Myc supports serine/glycine metabolism at the transcriptional level in other cell types (32, 33). These results suggest a model for breast cancer metastasis in which a small fraction of c-Mycbio expressing cells from the primary tumor acquire the ability to upregulate serine catabolism to fuel growth in metastatic tissue sites. Alternatively, high c-Myc expression and the linked ability to upregulate serine catabolism may be intrinsic properties of stem-like metastasis-initiating cells that are enriched in breast cancer cell populations selected for high metastatic activity in mice. As one of the key oncogenic transcription factors, there is increasing evidence that c-Myc plays multiple roles during the metastatic process. c-Myc knockdown reduces invasion and migration of MDA-MB-231 cells (30). Moreover, a recent study corroborated our findings of elevated c-Myc levels in brain-metastatic derivatives of human breast cancer cells and demonstrated its necessity for the invasive growth of brain metastases (45). Our study highlights the role of c-Myc in enhancing 1C unit pathway activity and proliferation, which is also important for metastatic growth. Because SHMT2 expression was not reduced by c-Myc shRNA, it is likely that other tumor-promoting factors, such as ATF4 and NRF2, also play important roles in late-stage cancer progression by modulating 1C unit metabolism. Intriguingly, a recent report showed that TGFβ signaling induces the expression of SHMT2 (46). Given the critical role of TGFβ in promoting metastasis (47, 48), it may be interesting to further investigate whether serine and 1C unit pathway metabolic reprogramming is controlled by TGFβ signaling in metastatic subpopulations of human breast cancer cells.

**Disclosure of Potential Conflicts of Interest**

J. Massagué is a scientific advisor for Scholar Rock, Inc., has received honoraria from speakers bureau of Skirball Institute, and is an unpaid consultant/advisory board member on the editorial boards of Cancer Discovery, Cell, EMBO J, Genes Dev and J. Cell Biol. J.D. Rabinowitz is founder/SAB of Raze Therapeutics and has ownership interest (including patents) in Princeton University. C.B. Thompson is a scientific advisory board member for Agios and Merck, is on the board of directors of Charles River Laboratories, and has ownership interest (including patents) in Agios, Merck, and Charles River Laboratories. No potential conflicts of interest were disclosed by the other authors.

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References
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