

Overexpression of initiator methionine tRNA leads to global reprogramming of tRNA expression and increased proliferation in human epithelial cells

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ABSTRACT

Transfer RNAs (tRNAs) are typically considered housekeeping products with little regulatory function. However, several studies over the past 10 years have linked tRNA misregulation to cancer. We have previously reported that tRNA levels are significantly elevated in breast cancer and multiple myeloma cells. To further investigate the cellular and physiological effects of tRNA overexpression, we overexpressed tRNA_i^{Met} in two human breast epithelial cell lines. We then determined tRNA abundance changes and performed phenotypic characterization. Overexpression of tRNA_i^{Met} significantly altered the global tRNA expression profile and resulted in increased cell metabolic activity and cell proliferation. Our results extend the relevance of tRNA overexpression in human cells and underscore the complexity of cellular regulation of tRNA expression.

Keywords: initiator methionine tRNA; tRNA; tRNA microarrays

INTRODUCTION

Misregulation of components of the translation machinery is characteristic of many types of tumor cells and can lead to malignant transformation (Bjornsti and Houghton 2004; Pandolfi 2004). Abnormally high levels of RNA polymerase III transcripts, including tRNA and 5S rRNA which are directly involved in translation, are found in a wide variety of transformed cell types (Marshall and White 2008). These cell types include cell lines transformed by DNA tumor viruses (such as hepatitis B virus), RNA tumor viruses (such as human T-cell leukemia virus 1), and chemical carcinogens. These observations have also been confirmed for tumors in situ by RT-PCR, Northern blot, and more recently by microarray analysis (Chen et al. 1997a,b; Winter et al. 2000; Pavon-Eternod et al. 2009). We have previously reported that tRNA levels are elevated in breast cancer and multiple myeloma cell lines (Pavon-Eternod et al. 2009; Zhou et al. 2009). Though abnormal RNA polymerase III activity has long been associated with cancer, it remains unclear whether it contributes to

malignant transformation or is simply a byproduct of the cell's cancer state.

Due to its unique function in translation initiation, we are particularly interested in the role of the initiator methionine tRNA (tRNA_i^{Met}) in cancer. An appealing possibility is that overexpression of tRNA_i^{Met} could alter the translational regulation of key genes involved in tumorigenesis. The effect may be both quantitative and qualitative: Overall protein synthesis may be increased, and mRNAs encoding cell-cycle or anti-apoptotic proteins (such as Myc or cyclin D1) may be preferentially translated. To explore this question in the context of breast cancer, we set out to overexpress tRNA_i^{Met} in human breast epithelial cell lines. Overexpressing tRNAs in human cell lines, however, proved more challenging than we had expected. Here we present our experimental approach to tRNA overexpression and a phenotypic characterization of the resulting cell lines (Fig. 1). We find that tRNA overexpression in human cells requires the generation of stable cell lines, and that only modest increases (1.4- to 2.2-fold) can be achieved. Remarkably, overexpression of tRNA_i^{Met} in both epithelial cell lines changed the levels of other tRNAs, reprogramming the global tRNA expression profile. tRNA_i^{Met} overexpression also resulted in increased metabolic activity and cell proliferation. Our results underscore the need for caution in interpreting the effects of individual tRNA overexpression, as little is known about the regulation of individual tRNA expression in the cell.

Abbreviations: tRNA_i^{Met}, initiator methionine tRNA; tRNA_c^{Met}, elongator methionine tRNA

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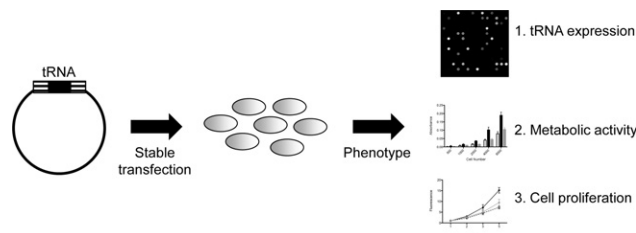


FIGURE 1. Experimental strategy for tRNA overexpression. The tRNA gene of interest with 200-bp flanking regions was cloned into a mammalian expression vector, then stably transfected into the human cell line. The stable cell line was then characterized in terms of tRNA expression profile, metabolic activity, and cell proliferation.

RESULTS AND DISCUSSION

Experimental strategies for tRNA overexpression

Because tRNAs are generally considered non-regulatory housekeeping genes, there are no well-established methods for manipulating the levels of specific tRNAs in mammalian cells. Furthermore, because tRNAs are highly abundant, overexpression even by twofold would require an additional transcription of $\sim 1,000,000$ molecules of $\text{tRNA}_i^{\text{Met}}$ per cell (Pavon-Eternod et al. 2009). In the past, exogenous tRNA has been introduced into cells either as DNA or directly as RNA (Carbon et al. 1983; Buvoli et al. 2000). We tried three different approaches to increase $\text{tRNA}_i^{\text{Met}}$ levels in two human cell lines: transient transfection with tRNA transcripts, transient transfection with a DNA vector containing the tRNA gene, and stable transfection with a DNA vector containing the tRNA gene. We selected the human breast epithelial cell lines 184A1 and MCF10A for these experiments for the following reasons: (i) They are non-tumorigenic cell lines, (ii) our previous work has shown 184A1 and MCF10A have relatively low levels of tRNA (Pavon-Eternod et al. 2009), and (iii) they are readily transfectable.

Our first approach relied on transient transfection of $\text{tRNA}_i^{\text{Met}}$ and $\text{tRNA}_c^{\text{Met}}$ transcripts. In vitro transcribed tRNAs have been reported to be active in translation when transfected into eukaryotic cells. Indeed, they have been used to insert unnatural amino acids into proteins and to induce amino acid substitutions resulting in widespread proteome damage in mammalian cells (Kohrer et al. 2001; Geslain et al. 2010). In vitro transcribed tRNAs are simple to synthesize and allow direct control over the amount of tRNA transfected. However, the question remains whether they are truly fully functional in the cell. In vitro transcribed tRNAs lack the post-transcriptional modifications characteristic of endogenous tRNAs that serve as identity determinants, contribute to tRNA stability, and impact translational accuracy (Alexandrov et al. 2006; Agris et al. 2007; Waas et al. 2007; Phizicky and Hopper 2010). This is particularly relevant for our tRNA of interest: $\text{tRNA}_i^{\text{Met}}$ transcripts lacking the m^1A_{58} modification are subject to nuclear polyadenylation and rapid

degradation (Kadaba et al. 2004, 2006; Vanacova et al. 2005). In any case, we found that in vitro transcribed tRNAs were toxic to MCF10A cells when transfected at high enough concentrations to detectably increase cellular tRNA levels (data not shown).

Our second approach relied on transient transfection of a DNA vector containing a $\text{tRNA}_i^{\text{Met}}$ or $\text{tRNA}_c^{\text{Met}}$ gene into MCF10A cells. Fragments containing the tRNA gene were PCR-amplified from human genomic DNA and cloned into the pTarget Mammalian Expression Vector. The fragments contained 200 base pairs each upstream of and downstream from the endogenous tRNA gene, which should include all the regulatory elements necessary for tRNA transcription (Geiduschek and Kassavetis 2001; Dieci et al. 2007). This approach is experimentally straightforward and allows the transfection of large amounts of DNA without inducing toxicity. High-copy plasmids have been successfully used to induce tRNA overexpression in yeast and bacteria (Borel et al. 1993; Anderson et al. 1998; Sorensen et al. 2005). Again, transfection with our tRNA vectors did not result in any detectable increase in tRNA levels (data not shown).

Our third approach involved the generation of stable cell lines after transfection with our $\text{tRNA}_i^{\text{Met}}$, $\text{tRNA}_c^{\text{Met}}$, and empty control vectors. Using this approach, we successfully generated an 184A1 cell line and an MCF10A cell line overexpressing $\text{tRNA}_i^{\text{Met}}$ relative to the control cell line (Fig. 2). From this point forward, we designate these cell lines 184A1- $\text{tRNA}_i^{\text{Met}}$ and MCF10A- $\text{tRNA}_i^{\text{Met}}$. The levels of $\text{tRNA}_i^{\text{Met}}$ increased by 1.4- and twofold, respectively, as measured by tRNA microarrays. This level is comparable to that observed in breast cancer cell lines relative to non-tumorigenic breast epithelial cell lines (Pavon-Eternod et al. 2009). We were, however, unable to generate either a 184A1 or MCF10A cell line overexpressing $\text{tRNA}_c^{\text{Met}}$ relative to the control cell line (Fig. 2A).

To confirm our microarray data, we analyzed $\text{tRNA}_i^{\text{Met}}$ and $\text{tRNA}_c^{\text{Met}}$ content in our 184A1 cell lines (control, 184A1- $\text{tRNA}_i^{\text{Met}}$, and MCF10A- $\text{tRNA}_i^{\text{Met}}$) by dot blot (Fig. 2B). In all cases, the microarray and dot blot data were in very good agreement. Our selective fluorophore labeling method requires that all tRNAs measured by microarrays contain 3'CCA (Pavon-Eternod et al. 2009) which is characteristic of all mature tRNAs. The agreement between microarray, which measures mature tRNA, and dot blot data, which measure mature and precursor tRNA, indicates that the observed $\text{tRNA}_i^{\text{Met}}$ overexpression is primarily derived from mature tRNA.

$\text{tRNA}_i^{\text{Met}}$ overexpression generates unique tRNA expression profiles

Unexpectedly, $\text{tRNA}_i^{\text{Met}}$ overexpression induced a significant change in the levels of other tRNAs. Compared with the corresponding control line, median nuclear-encoded tRNA abundance increased by 1.4-fold in 184A1- $\text{tRNA}_i^{\text{Met}}$ and 2.2-fold in MCF10A- $\text{tRNA}_i^{\text{Met}}$, whereas median mitochondrial-

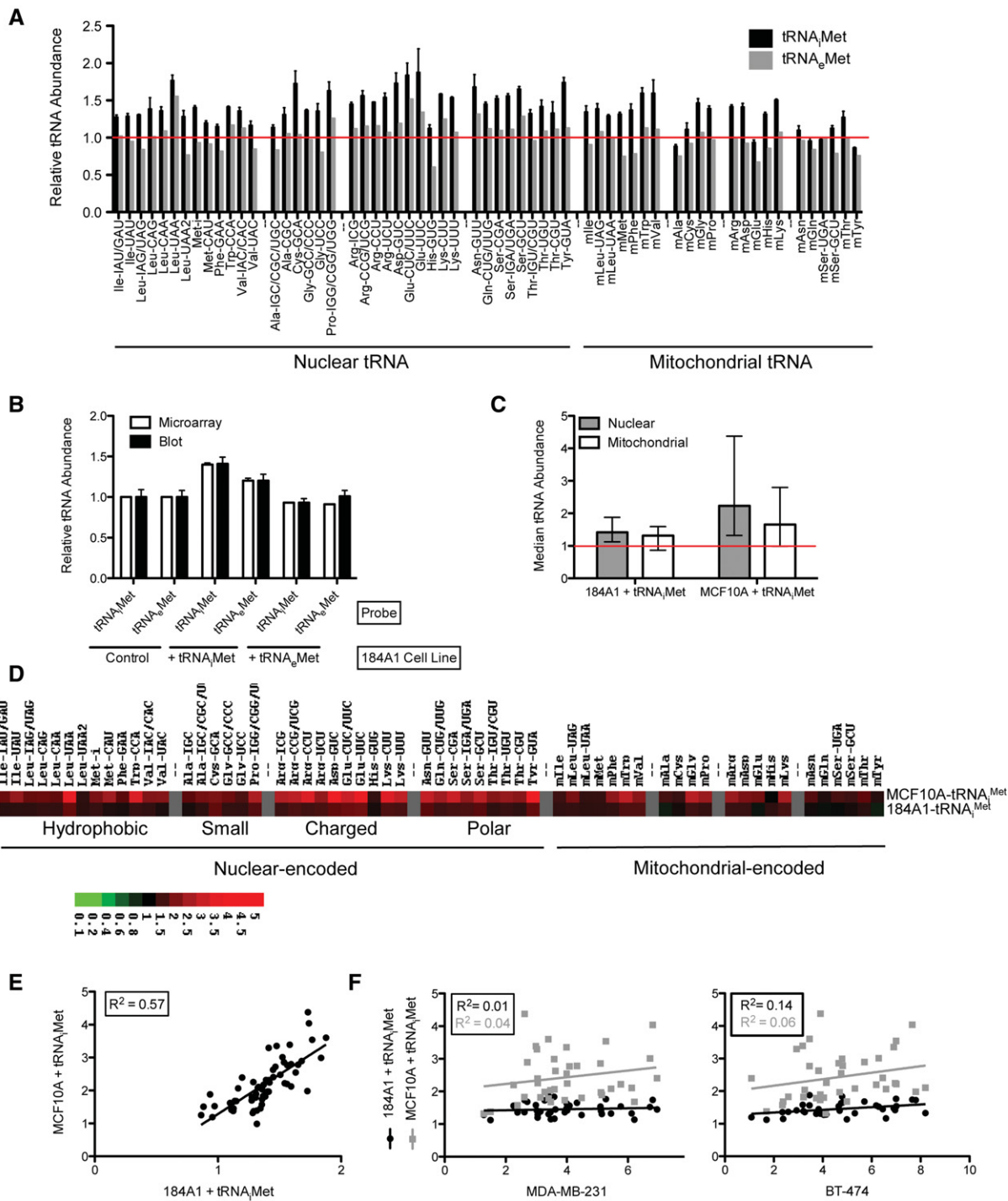


FIGURE 2. tRNA^{Met} overexpression generates unique tRNA expression profiles. (A) Individual tRNA abundances in 184A1-tRNA_i^{Met} and 184A1-tRNA_e^{Met} cell lines. Individual tRNA abundance values are shown for 184A1-tRNA_i^{Met} (black) and 184A1-tRNA_e^{Met} (gray) relative to an empty vector control cell line (set to 1, red line). A value of 1 indicates no change, a value <1 indicates a decrease, and a value >1 indicates an increase in tRNA levels relative to the control cell line. Data are grouped according to amino acid type. The tRNA_i^{Met} and tRNA_e^{Met} probes are labeled Met-i and Met-CAU, respectively. Where error bars are present, values are averages from dye-swapped experiments and error bars indicate standard deviation. One sample *t*-test was performed to determine the statistical significance of the changes: **P*-value <0.05. (B) Validation of microarray data by dot blot. As in A, relative tRNA abundance is defined as the ratio between the indicated cell line and the control cell line. Relative tRNA abundance values obtained by microarray (white) and dot blot (black, average of three replicates, error bars indicate standard deviation) are plotted for tRNA_i^{Met} and tRNA_e^{Met} in the three 184A1 cell lines generated for this study (control, 184A1-tRNA_i^{Met} and 184A1-tRNA_e^{Met}). (C) Median tRNA abundance upon tRNA_i^{Met} overexpression. Median values for 184A1-tRNA_i^{Met} and MCF10A-tRNA_i^{Met} relative to control cell lines (set to 1, red line). Median values for nuclear-encoded tRNAs (gray) and mitochondrial-encoded (white) tRNAs are shown. The upper and lower bars indicate the range of individual tRNA abundances. (D) Heat map of tRNA abundances upon tRNA_i^{Met} overexpression. Relative tRNA abundance levels of nuclear and mitochondrial-encoded tRNAs in 184A1-tRNA_i^{Met} and MCF10A-tRNA_i^{Met} are shown as TreeView images. Data are grouped according to amino acid type. Green indicates a decreased level of expression, red indicates an increased level of expression, and black indicates no change in expression level relative to the reference sample. (E) Individual tRNA abundances in 184A1-tRNA_i^{Met} compared with MCF10A-tRNA_i^{Met}. Individual tRNA abundance values for 184A1-tRNA_i^{Met} and MCF10A-tRNA_i^{Met} are relative to the corresponding control cell lines. (F) Individual nuclear-encoded tRNA abundances in two breast cancer cell lines, MDA-MB-231 (left) and BT-474 (right) compared with 184A1-tRNA_i^{Met} and MCF10A-tRNA_i^{Met}. Individual tRNA levels for the two breast cancer cell lines, MDA-MB-231 and BT-474, are relative to the breast epithelial MCF10A cell line. Individual tRNA levels for the 184A1-tRNA_i^{Met} and MCF10A-tRNA_i^{Met} cell lines are relative to the corresponding control cell lines.

encoded tRNA abundance increased by 1.3-fold in 184A1-tRNA^{Met}_i and 1.7-fold in MCF10A-tRNA^{Met}_i (Fig. 2C). These changes are more striking for individual tRNAs (Fig. 2A,D). Due to the nature of our microarray measurements, we express individual tRNA abundances in 184A1-tRNA^{Met}_i and MCF10A-tRNA^{Met}_i relative to the corresponding control cell line. While some tRNAs are increased up to fourfold upon tRNA^{Met}_i overexpression, others are not affected. Remarkably, tRNA^{Met}_i overexpression generates very similarly altered expression profiles for nuclear-encoded tRNAs in both 184A1 and MCF10A cell lines ($R^2 = 0.57$, Fig. 2E).

We also compared whether the tRNA expression profiles induced by tRNA^{Met}_i overexpression in breast epithelial lines are similar to those measured in breast cancer cell lines. Our previous study of tRNA expression in breast cancer revealed that tRNA overexpression is characteristic of breast cancer cells, and that this overexpression is highly selective based on tRNA identity (Pavon-Eternod et al. 2009). We therefore plotted tRNA levels (relative to the breast epithelial cell line MCF10A) in two breast cancer cell lines, MDA-MB-231 and BT-474, vs. the tRNA levels (relative to the corresponding control cell line) in our 184A1-tRNA^{Met}_i and MCF10A-tRNA^{Met}_i cell lines. We find a very poor correlation between the tRNA levels in bona fide breast cancer cell lines and the tRNA levels induced by tRNA^{Met}_i overexpression ($R^2 < 0.15$ in all cases) (Fig. 2F). While the tRNAs carrying charged and polar amino acids were consistently among the most overexpressed tRNAs in the breast cancer cell lines examined, we observe no such trends in our 184A1-tRNA^{Met}_i and MCF10A-tRNA^{Met}_i lines.

Initiator methionine tRNA overexpression leads to increased cell metabolism and proliferation

Elevated tRNA levels are characteristic of breast cancer cells (Pavon-Eternod et al. 2009) which often exhibit altered metabolic activity and unregulated growth compared with non-cancer cells. We therefore measured the metabolic activity and cell proliferation of 184A1-tRNA^{Met}_i relative to the 184A1-control cell line (Fig. 3). We also included the 184A1-tRNA^{Met}_e cell line as an additional control: Even though tRNA^{Met}_e expression was not increased in this line as we had expected, we detected punctual changes in the levels of several other tRNAs (such as tRNA^{Leu(UAA)} and tRNA^{Glu(CUC/UUC)}) (Fig. 2A), which may have an effect. We first measured the metabolic activity using two assays: Calcein AM, which relies on the activity of cytoplasmic esterases, and WST1, which relies on the activity of mitochondrial dehydrogenases. Both assays showed increased metabolic activity for 184A1-tRNA^{Met}_i relative the control cell line, but no change in metabolic activity for 184A1-tRNA^{Met}_e. We also measured cell proliferation by Hoechst staining. Again, 184A1-tRNA^{Met}_i showed increased cell proliferation relative to the control cell line, but no significant change was seen for 184A1-tRNA^{Met}_e.

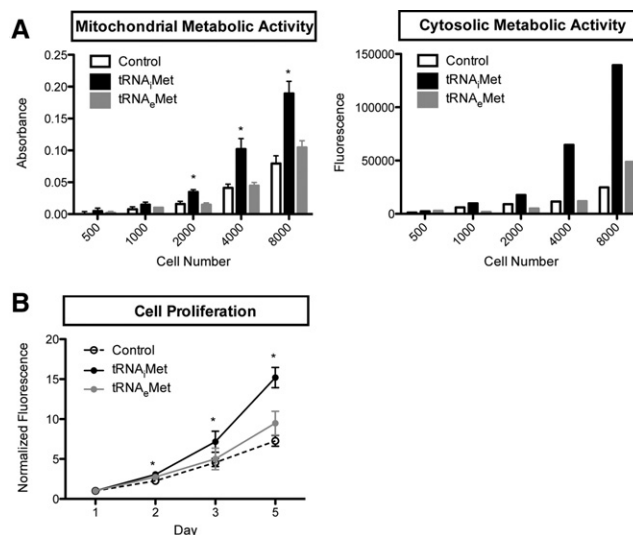


FIGURE 3. tRNA^{Met}_i overexpression leads to increased cell metabolism and proliferation. Data are shown for the 184A1 cell lines 184A1-control, 184A1-tRNA^{Met}_i, and 184A1-tRNA^{Met}_e. *T*-tests were performed to determine the statistical significance of the differences observed relative to 184A1-control: **P*-value < 0.05. (A) Metabolic activity. Mitochondrial metabolic activity was measured by WST1, which relies on the activity of mitochondrial dehydrogenases. Cytosolic metabolic activity was measured by Calcein AM, which relies on the activity of cytoplasmic esterases. Where error bars are indicated, assays were performed in triplicate and the error bars indicate standard deviation. (B) Cell proliferation. Cell proliferation was measured over 5 d by Hoechst DNA staining. The assays were performed in triplicate; error bars indicate standard deviation.

Concluding remarks

In our experience, overexpressing a specific tRNA in human cell lines is not trivial. Of three possible approaches attempted by us, only one was successful: the generation of stable cell lines after transfection with a DNA vector containing the tRNA gene. Even so, we were able to generate cell lines stably overexpressing the desired tRNA for only one of two tRNAs. While we successfully generated stable cell lines overexpressing tRNA^{Met}_i, we were unable to generate stable cell lines overexpressing tRNA^{Met}_e to any detectable level. This may be due to some intrinsic properties of tRNA^{Met}_e, or other random factors such as the site of integration and copy number. Our results also indicate that manipulating the levels of one specific tRNA—in this case tRNA^{Met}_i—significantly affects the levels of other tRNAs in the cell, suggesting some kind of feedback regulatory mechanism in the cell. Remarkably, tRNA^{Met}_i overexpression in two different cell lines resulted in similar patterns of tRNA expression. We expect that the tRNA expression profile induced by overexpressing a specific tRNA is dependent on many factors, including but not limited to the identity of the tRNA being introduced, the genetic background of the cell, and the integration sites. Regardless, care must be taken in attributing phenotypic changes to overexpression of an individual tRNA. The increase in metabolic

activity and cell proliferation we measure in our 184A1-tRNA_i^{Met} cell line may indeed be due to tRNA_i^{Met} overexpression, but also to overexpression of a number of other tRNAs or even to globally increased tRNA levels.

Our findings highlight the fact that little is known about the regulation of individual tRNA expression in the cell, and how cells respond to perturbations in tRNA levels. It is generally believed that tRNA transcription via RNA polymerase III is globally regulated in response to nutrient availability and other environmental signals, in coordination with rRNA transcription via RNA polymerase I. Current models hold that transcription at tRNA genes is coordinately regulated by shared transcription factors, acting at highly related promoter sequences (Phizicky and Hopper 2010). This view does not account for the tissue-specific differences in individual tRNA expression or the differential overexpression of individual tRNA species in breast cancer cells (Dittmar et al. 2006; Pavon-Eternod et al. 2009). A systematic study of individual tRNA expression is required to elucidate the functional significance and underlying regulatory mechanisms.

MATERIALS AND METHODS

DNA vectors

Fragments containing tRNA genes were PCR-amplified from human genomic DNA, using the following primer pairs: 5'-TGAG TTGGCAACCTGTGGTA and 5'-TTGGGTGTCCATGAAAATCA for tRNA_i^{Met}, 5'-AGCGACCTTCCCACA and 5'-GTCTCCATT CCTACACG for tRNA_e^{Met}. These fragments were cloned into the pTarget Mammalian Expression vector (Promega) following the manufacturer's instructions.

Cell lines

All cell lines were purchased from American Type Culture Collection (ATCC). MCF10A and 184A1 cells were cultured in 1:1 DMEM/F12 with 2.5 mM L-Gln and 15 mM HEPES (Thermo Scientific HyClone) supplemented with 10% FBS, 1% Penicillin/Streptomycin, 5 µg/mL insulin, 10 ng/mL EGF, and 0.5 µg/mL hydrocortisone. MDA-MB-231 and BT-474 were cultured in RPMI 1640 1× medium (Thermo Scientific HyClone) supplemented with 10% FBS and 1% Penicillin/Streptomycin.

To generate stable cell lines, cells were transfected using Amaxa Nucleofector technology (LonzaBio). After 48 h, medium was supplemented with 500 µg/mL G418 (Sigma) for selection. After 2–4 wk, G418 resistant colonies appeared and the G418 concentration was scaled down to 200 µg/mL. Medium was supplemented with 200 µg/mL G418 for routine culture.

Transfer RNA microarrays

Total RNA for each cell line was obtained at 80%–90% confluency using the miRVana miRNA Isolation Kit (Ambion). This procedure isolates RNA species as short as 15 nt and is therefore not biased against tRNA. Total RNA quality was verified by agarose gel electrophoresis.

The tRNA microarray experiment consists of four steps starting from total RNA: (1) deacylation to remove any amino acids still attached to the tRNA, (2) selective fluorophore labeling of tRNA, (3) hybridization, and (4) data analysis. The tRNA microarray method, including reproducibility and result validation by Northern blot, has been extensively described in previously published papers (Dittmar et al. 2004, 2006; Pavon-Eternod et al. 2009, 2010; Zhou et al. 2009).

Dot blots

The following DNA probes, identical to those spotted on the tRNA microarrays, were used to quantify tRNA_i^{Met} and tRNA_e^{Met} in total RNA: 5'-AGCAGAGTGGCGCAGCGGAAGCGTGCTGGGCCAT AACCAGAGGTCGATGGATCGAAACCATCCTCTGCTA-3' for tRNA_i^{Met}, and 5'-GCCYYCTTAGCGCAGYDGGCAGCGCGTCA GTCTCATAATCTGAAGGTCCTGAGTTCGAGCCTCAGAGRGGG CA-3' for tRNA_e^{Met}. Probes were 5'-radiolabeled using T4 polynucleotide kinase and γ-³²P-ATP (Perkin-Elmer), followed by purification on a denaturing urea polyacrylamide gel. To detect tRNA_i^{Met} and tRNA_e^{Met} in total RNA, 100 ng total RNA was spotted and UV cross-linked on a Hybond XL membrane (GE Healthcare). The membrane was pre-hybridized in hybridization buffer (300 mM NaCl, 1% SDS, 20 mM phosphate buffer pH 7) for 30 min at room temperature, then hybridized overnight at 60°C in hybridization buffer containing 100,000–300,000 cpm of the radiolabeled probe. The membrane was then washed three times for 20 min at room temperature in wash buffer (300 mM NaCl, 0.1% SDS, 20 mM phosphate buffer pH 7, 2 mM EDTA). Phosphorimaging was used to quantify the amount of tRNA_i^{Met} and tRNA_e^{Met} present in each sample.

Metabolic activity assays

Cells were plated in 100 µL medium in 96-well plate at the following cell densities: 500, 1000, 2000, 4000, and 8000 cells/well. For WST1 assays: 10 µL WST1 reagent (Roche 05 015 944 001) was added to each well. Absorbance at 440 nm was read after 1 h incubation at 37°C. For Calcein AM assays: Cells were incubated in 200 µL Calcein AM (BD 354216) working solution (1 µM in HBSS) for 1 h at 37°C. Fluorescence was measured at 490ex/520em.

Cell proliferation assays

Cell proliferation was measured over 5 d using Hoechst DNA staining (Invitrogen H1398). Cells were plated in 100 µL medium at 500 cells/well in 96-well plates. To stain DNA, cells were incubated in 100 µL of 0.1 µg/mL Hoechst solution in HBSS for 1 h at 37°C. After washing with HBSS to remove any unbound dye, fluorescence was measured 355ex/460em. Fluorescence is directly proportional to the number of cells present, regardless of cell type.

Statistical significance

T-tests and one-sample t-tests were performed using GraphPad QuickCalcs (<http://www.graphpad.com/quickcalcs/contMenu/>).

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