Differential expression of ribonucleotide reductase regulatory subunit M2 in triple negative breast cancer.

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Women diagnosed with triple negative breast cancer can benefit neither from endocrine therapy nor from HER2-targeted therapies¹. We mined published microarray datasets^{2,3} to determine in an unbiased fashion and at the systems level genes most differentially expressed in the primary tumors of patients with breast cancer. We report here significant differential expression of the gene encoding ribonucleotide reductase regulatory subunit M2, RRM2, when comparing the tumor cells of patients with triple negative breast cancer to normal mammary ductal cells². RRM2 was also differentially expressed in bulk tumor in human breast cancer³. RRM2 mRNA was present at significantly increased quantities in TNBC tumor cells relative to normal mammary ductal cells. Analysis of human survival data revealed that expression of RRM2 in primary tumors of the breast was correlated with recurrence-free survival in patients with luminal A type cancer, while within triple negative breast cancer, primary tumor expression of RRM2 was correlated with distant metastasis-free survival in patients with luminal androgen receptor subtype disease. RRM2 may be of relevance to initiation, maintenance or progression of triple negative breast cancers.

Keywords: breast cancer, RRM2, ribonucleotide reductase regulatory subunit M2, systems biology of breast cancer, targeted therapeutics in breast cancer.

Patients with hormone receptor positive disease can benefit from endocrine therapy⁴: aromatase inhibition such as that provided by exemestane or letrozole, or estrogen receptor antagonism such as that provided by tamoxifen or fulvestrant. Patients whose tumors overexpress the human epidermal growth factor 2 (HER2) can be treated with HER2-targeted therapies: HER2 inhibitors, immunoglobulin⁵- or small molecule-based⁶. As triple negative breast cancer (TNBC) is defined by its lack of HER2 expression as well as by its lack of expression of the hormone receptor estrogen, patients diagnosed with triple negative breast cancer will not benefit from either of these treatment strategies.

Understanding the transcriptional composition of triple negative breast cancers in humans can facilitate development of novel therapeutics and contribute to efforts to prevent progression to metastatic stages. We mined published microarray data^{2,3} to understand at the transcriptome level and in an unbiased fashion genes most differentially expressed in the tumor cells of patients with triple negative breast cancer.

Methods

We utilized datasets GSE38959² and GSE109169³ for this differential gene expression analysis of female breast cancer in conjunction with GEO2R. GSE38959 was generated using Agilent-014850 Whole Human Genome Microarray 4x44K G4112F technology with $n=13$ samples of normal mammary gland ductal cells and $n=30$ samples of tumor cells from patients with triple negative breast cancer; analysis was performed using platform GPL4133. GSE109169 was generated using Affymetrix Human Exon 1.0 ST Array technology with $n=25$ normal breast tissue and $n=25$ tumors of the breast; analysis was performed using platform GPL5175. The tissues from this dataset are paired tissues (25 tumors matching 25 normal breast tissues from 25 patients). The Benjamini and Hochberg method of p -value adjustment was used for ranking of differential expression but raw p -values were used to assess statistical significance of global differential expression. Log-transformation of data was auto-detected, and the NCBI-generated category of platform annotation was used. A statistical test was performed to evaluate whether RRM2 expression was significantly different between primary breast tumors and breast tissue using a two-tailed t-test.

For Kaplan-Meier survival analysis, we used the Kaplan-Meier plotter tool⁷ for correlation of RRM2 mRNA expression levels with recurrence-free survival (RFS) in $n=431$ patients with basal subtype cancer, $n=596$ patients with luminal A subtype cancer, $n=439$ patients with luminal B subtype cancer, $n=362$ patients with HER2+ cancer, and $n=51$ patients with normal-like subtype cancer. In patients with triple negative breast cancer⁷, we analyzed distant metastasis-free survival (DMFS) for $n=171$ patients with basal-like 1 subtype TNBC, $n=71$ patients with basal-like 2 subtype TNBC, $n=219$ patients with immunomodulatory subtype TNBC, $n=138$ patients with luminal androgen receptor subtype TNBC, $n=130$ patients with mesenchymal subtype TNBC, and $n=39$ patients with mesenchymal stem-like subtype TNBC.

Results

We performed discovery of genes associated with triple negative breast cancer in humans by mining two independently published microarray datasets^{2,3}.

RRM2 is differentially expressed in primary tumors and tumor cells of the breast.

Comparison of the tumor cells of patients with triple negative breast cancer to normal mammary ductal cells² revealed ribonucleotide reductase regulatory subunit M2, encoded by RRM2, as among the genes whose expression was most significantly different in human TNBC as compared to the normal breast (Chart 1). When sorting each of the genes expressed in the tumor cells of patients with triple negative breast cancer based on significance of difference as compared to normal mammary ductal cells, RRM2 ranked 46 out of 45015 total transcripts, equating to 99.9% differential expression (Chart 1). Differential expression of RRM2 in the tumor cells of patients with triple negative breast cancer was statistically significant (Chart 1; $p=5.59\text{E-}14$).

Analysis of a second microarray dataset³, here comparing 25 normal breast tissues to 25 tumors of the breast revealed that RRM2 was also among the genes most differentially expressed in human breast cancer, here in the tumors of women diagnosed with early-onset breast cancer (Chart 2). When sorting each of the genes expressed in tumors of the breast based on significance of difference as compared to normal breast tissue, RRM2 ranked 1047 out of 19076 total transcripts, equating to 94.5% differential expression (Chart 2). Differential expression of RRM2 in female breast cancer was statistically significant (Chart 2; $p=8.59E-09$).

These data indicated that differential expression of RRM2 was not an artifact of a single microarray dataset, was not an artifact of FACS isolation, and suggested that perturbed expression of RRM2 was likely a transcriptional feature of triple negative breast cancers and early-onset human breast cancers.

RRM2 is expressed at significantly higher levels in triple negative tumor cells as compared to normal cells of the breast.

We obtained exact mRNA expression levels for RRM2 - from normal mammary ductal cells of the breast and from tumor cells of patients with triple negative breast cancer - to understand the magnitude and direction of RRM2 expression change in TNBC. RRM2 mRNA transcript was present at higher levels in triple negative tumor cells of the breast as compared to normal mammary ductal cells (Figure 1). Increased expression of RRM2 in primary tumor-isolated triple negative breast cancer cells was statistically significant (Figure 1: $p<0.0001$). RRM2 was expressed at 24.18 ± 29.22 arbitrary units (A.U.) in normal mammary ductal cells, while it was expressed at 229.43 ± 122.81 A.U. in tumor cells of patients with triple negative breast cancer. We calculated a mean fold change of 9.49 when comparing triple negative breast cancer cells to normal mammary ductal cells.

RRM2 expression correlates with survival outcomes in luminal A human breast cancer.

We performed Kaplan-Meier survival analysis to evaluate potential relationships between primary tumor RRM2 mRNA expression levels and survival outcomes in patients with breast cancer, when analyzing outcomes based on the molecular subtype of the patient (PAM50 classification): luminal A, luminal B, HER2+, normal-like, and basal-like. We observed a correlation between RRM2 expression and recurrence-free survival (RFS) in patients with luminal A subtype breast cancer that trended towards statistical significance (Figure 2; log rank p -value: 0.096 for recurrence-free survival, hazard ratio: 1.44 (0.94-2.21) (Fig. 2)). RRM2 mRNA levels were a negative prognostic indicator in luminal A breast cancer patients. Median RFS was 175.46 months for luminal A patients with low tumor expression of RRM2 while median RFS was 173.72 months for luminal A patients with high tumor expression of RRM2 (Chart 3).

RRM2 primary tumor expression was not correlated with recurrence-free survival in basal subtype (Figure 2; log rank p -value: 0.98 for RFS, hazard ratio: 1.01 (0.69-1.47) (Fig. 2), luminal B subtype (Figure 2; log rank p -value: 0.41 for RFS, hazard ratio: 1.16 (0.82-1.65) (Fig. 2)), in HER2+ breast cancer (Figure 2; log rank p -value: 0.38 for RFS, hazard ratio: 1.19 (0.81-1.75) (Fig. 2)), or in the normal-like subtype (Figure 2; log rank p -value: 0.4 for RFS, hazard ratio: 1.52 (0.57-4.09) (Fig. 2)).

Influence of primary tumor RRM2 expression on survival outcomes based on TNBC molecular subtype.

We also performed Kaplan-Meier survival analysis to examine relationships between RRM2 mRNA expression levels with survival strictly in patients with triple negative breast cancer, analyzing outcomes based on the TNBC molecular subtype⁸ of the patient: basal-like 1, basal-like 2,

immunomodulatory, mesenchymal, mesenchymal stem-like, and luminal androgen receptor. We observed a statistically significant correlation between RRM2 expression and distant metastasis-free survival (DMFS) in TNBC patients with luminal androgen receptor subtype disease (Figure 3; log rank p -value: 0.036 for distant metastasis-free survival, hazard ratio: 0.54 (0.3-0.97) (Fig. 3)). RRM2 mRNA levels were a positive prognostic indicator in patients with luminal androgen receptor TNBC. Median DMFS was 24.31 months for luminal androgen receptor TNBC patients with low tumor expression of RRM2 while median DMFS was 57.3 months for luminal androgen receptor TNBC patients with high tumor expression of RRM2 (Chart 4).

RRM2 primary tumor expression was not correlated with distant metastasis-free survival in the basal-like 1 subtype (Figure 3; log rank p -value: 0.3 for DMFS, hazard ratio: 1.35 (0.76-2.39) (Fig. 3)), basal-like 2 subtype (Figure 3; log rank p -value: 0.72 for DMFS, hazard ratio: 1.15 (0.54-2.45) (Fig. 3), immunomodulatory subtype (Figure 3; log rank p -value: 0.98 for DMFS, hazard ratio: 1.01 (0.59-1.74) (Fig. 3)), in the mesenchymal subtype (Figure 3; log rank p -value: 0.54 for DMFS, hazard ratio: 0.83 (0.46-1.5) (Fig. 3)), or in the mesenchymal stem-like subtype (Figure 3; log rank p -value: 0.99 for DMFS, hazard ratio: 1.01 (0.36-2.81) (Fig. 3)).

Discussion

We performed comparative transcriptome analysis using two independently published microarray datasets^{2,3} to define and catalog transcriptional differences in human triple negative breast cancer. We provided evidence here that differential expression of ribonucleotide reductase regulatory subunit M2, encoded by the RRM2 gene, is a defining transcriptional feature of triple negative breast cancer. RRM2 was also differentially expressed in the bulk tumors of patients with early-onset breast cancer. Expression of RRM2 was correlated with recurrence-free survival in patients with luminal A subtype breast cancer, and within triple negative breast cancer patients, primary tumor expression of RRM2 was correlated with distant metastasis-free survival in patients with luminal androgen receptor subtype disease. Ribonucleotide reductase regulatory subunit M2 and the molecular processes to which it pertains to may be relevant to the initiation or progression of triple negative breast cancer in humans.

References

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Rank: 46
Probe ID: 21855
p-value: 5.59E-14
t: -10.7075668
B: 21.64922
Gene: RRM2
Gene name: ribonucleotide reductase regulatory subunit M2

Chart 1: RRM2 is differentially expressed in triple negative breast cancer.

Rank of differential expression, probe ID, p-value of global differential expression, t, a moderated t-statistic, B, the log-odds of differential expression between the groups compared, gene and gene name are listed in this chart.

Rank: 1047
Probe ID: 2469252
p-value: 8.59E-09
t: -6.87
B: 9.861574
Gene: RRM2
Gene name: ribonucleotide reductase regulatory subunit M2

Chart 2: RRM2 is differentially expressed in early-onset human breast cancer.

Rank of differential expression, probe ID, p-value of global differential expression, t, a moderated t-statistic, B, the log-odds of differential expression between the groups compared, gene and gene name are listed in this chart.

Figure 1: RRM2 is expressed at significantly higher levels in primary TNBC tumor cells as compared to normal cells of the breast.

The mRNA expression level of RRM2 in normal mammary ductal cells (left) and in the isolated primary tumor cells of patients with triple negative breast cancer (right) is graphically depicted with the result of a statistical test evaluating significance of difference in RRM2 expression between normal cells of the breast and TNBC tumor cells, a p -value, listed above.

Figure 2: RRM2 expression correlates with recurrence-free survival in patients with luminal A breast cancer, but not in patients with basal, luminal B, HER2+, or normal-like subtype cancer.

Depicted in this Kaplan-Meier plot is the probability of recurrence-free survival (RFS) for $n=431$ patients with basal subtype breast cancer (upper left), $n=362$ patients with HER2+ breast cancer (upper right), $n=596$ patients with luminal A breast cancer (middle left), $n=439$ patients with luminal B breast cancer (middle right), and $n=51$ patients with normal-like breast cancer (below) stratified into two groups, based on low or high expression of RRM2 in patient primary tumors. The log rank p -value denoting statistical significance of difference in recurrence-free survival when comparing the two groups, as well as hazard ratio for this comparison is listed above. Listed below is the number of patients at risk (number of patients alive) per interval, after stratification based on RRM2 expression; in the first interval, number at risk is number of patients alive; in each subsequent interval, number at risk is the number at risk less those who have expired or are censored.

1 Low RRM2 expression: 175.46 months

2 High RRM2 expression: 173.72 months

3 **Chart 3: Median recurrence-free survival is superior in luminal A subtype breast cancer patients**
4 **with low primary tumor expression of RRM2.**

5 The recurrence-free survival of $n=596$ luminal A subtype breast cancer patients based on stratification into
6 low or high tumor expression of RRM2 is listed in this chart.

Figure 3: RRM2 expression correlates with distant metastasis-free survival in triple negative breast cancer patients whose tumors are of the luminal androgen receptor molecular subtype.

Depicted in this Kaplan-Meier plot is the probability of distant metastasis-free survival (DMFS) for $n=171$ patients with basal-like 1 subtype TNBC (upper left), $n=71$ patients with basal-like 2 subtype TNBC (upper right), $n=219$ patients with immunomodulatory subtype TNBC (middle left), $n=138$ patients with luminal androgen receptor subtype TNBC (middle right), $n=130$ patients with mesenchymal subtype TNBC (lower left), and $n=39$ patients with mesenchymal stem-like subtype TNBC (lower right), stratified into two groups, based on low or high expression of RRM2 in the primary tumors of patients with TNBC. The log rank p-value denoting statistical significance of difference in distant metastasis-free survival when comparing the two groups, as well as hazard ratio for this comparison is listed above. Listed below is the number of patients at risk (number of patients alive) per interval, after stratification based on RRM2 expression; in the first interval, number at risk is number of patients alive; in each subsequent interval, number at risk is the number at risk less those who have expired or are censored.

1 Low RRM2 expression: 24.31 months

2 High RRM2 expression: 57.3 months

3 **Chart 4: In patients with luminal androgen receptor subtype disease, median distant metastasis-free**
4 **survival is superior in triple negative breast cancer patients with high primary tumor expression of**
5 **RRM2.**

6 The distant metastasis-free survival of $n=138$ luminal androgen receptor subtype TNBC patients based on
7 stratification into low or high tumor expression of RRM2 is listed in this chart.