Differential expression of structural maintenance of chromosomes 4 in triple negative breast cancer.

Shahan Mamoor, MS¹

¹shahanmamoor@gmail.com

East Islip, NY 11730

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 structural maintenance of chromosomes 4, SMC4, when comparing the tumor cells of patients with triple negative breast cancer to normal mammary ductal cells². SMC4 was also differentially expressed in bulk tumor in human breast cancer³. SMC4 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 SMC4 in primary tumors of the breast was correlated with overall survival in patients with basal-like type cancer, while within triple negative breast cancer, primary tumor expression of SMC4 was correlated with overall survival in patients with mesenchymal, mesenchymal stem-like, and luminal androgen receptor subtype disease. SMC4 may be of relevance to initiation, maintenance or progression of triple negative breast cancers.

Keywords: breast cancer, SMC4, structural maintenance of chromosomes 4, 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 SMC4 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 SMC4 mRNA expression levels with overall survival (OS) in $n=431$ patients with luminal A subtype cancer, $n=596$ patients with luminal B subtype cancer, $n=439$ patients with basal-like 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 overall survival (OS) for $n=103$ patients with basal-like 1 subtype TNBC, $n=58$ patients with basal-like 2 subtype TNBC, $n=149$ patients with immunomodulatory subtype TNBC, $n=116$ patients with luminal androgen receptor subtype TNBC, $n=114$ patients with mesenchymal subtype TNBC, and $n=39$ patients with mesenchymal stem-like subtype TNBC, in the lower quartile.

Results

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

SMC4 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 structural maintenance of chromosomes 4, encoded by SMC4, 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, SMC4 ranked 90 out of 45015 total transcripts, equating to 99.8% differential expression (Chart 1). Differential expression of SMC4 in the tumor cells of patients with triple negative breast cancer was statistically significant (Chart 1; $p=6.14E-13$).

Analysis of a second microarray dataset³, here comparing 25 normal breast tissues to 25 tumors of the breast revealed that SMC4 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, SMC4 ranked 531 out of 19076 total transcripts, equating to 97.2% differential expression (Chart 2). Differential expression of SMC4 in female breast cancer was statistically significant (Chart 2; $p=1.40E-10$).

These data indicated that differential expression of SMC4 was not an artifact of a single microarray dataset, was not an artifact of laser microdissection, and suggested that perturbed expression of SMC4 was likely a transcriptional feature of triple negative breast cancers and early-onset human breast cancers.

SMC4 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 SMC4 - 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 SMC4 expression change in TNBC. SMC4 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 SMC4 in primary tumor-isolated triple negative breast cancer cells was statistically significant (Figure 1: $p<0.0001$). SMC4 was expressed at 304.3 ± 332.9 arbitrary units (A.U.) in normal mammary ductal cells, while it was expressed at 1467.8 ± 671.8 A.U. in tumor cells of patients with triple negative breast cancer. We calculated a mean fold change of 4.82 when comparing triple negative breast cancer cells to normal mammary ductal cells.

SMC4 expression correlates with survival outcomes in basal-like human breast cancer.

We performed Kaplan-Meier survival analysis to evaluate potential relationships between primary tumor SMC4 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 statistically significant correlation between SMC4 expression and overall survival (OS) in patients with basal-like subtype breast cancer (Figure 2; log rank p -value: 0.01 for overall survival, hazard ratio: 0.6 (0.41-0.89) (Fig. 2)).

SMC4 mRNA levels were a positive prognostic indicator in basal-like breast cancer patients. Median OS was 57.53 months for basal-like patients with low tumor expression of SMC4 while median OS was 115 months for basal-like patients with high tumor expression of SMC4 (Chart 3).

SMC4 primary tumor expression was not correlated with overall survival in luminal A subtype (Figure 2; log rank p -value: 0.15 for OS, hazard ratio: 1.37 (0.89-2.09) (Fig. 2), luminal B subtype (Figure 2; log rank p -value: 0.37 for OS, hazard ratio: 1.17 (0.83-1.67) (Fig. 2)), in HER2+ breast cancer (Figure 2; log rank p -value: 0.36 for OS, hazard ratio: 0.84 (0.57-1.23) (Fig. 2)), or in the normal-like subtype (Figure 2; log rank p -value: 0.65 for OS, hazard ratio: 1.26 (0.47-3.37) (Fig. 2)).

Influence of primary tumor SMC4 expression on survival outcomes based on TNBC molecular subtype.

We also performed Kaplan-Meier survival analysis to examine relationships between SMC4 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 SMC4 expression and overall survival (OS) in TNBC patients with mesenchymal subtype disease, in the lower quartile (Figure 3; log rank p -value: 0.0049 for overall survival, hazard ratio: 0.5 (0.25-1.01) (Fig. 3)). SMC4 mRNA levels were a positive prognostic indicator in patients with mesenchymal TNBC. Median OS 30.31 months for mesenchymal TNBC patients with low tumor expression of SMC4 while median OS was 56.4 months for mesenchymal TNBC patients with high tumor expression of SMC4 (Chart 4).

We also observed a statistically significant correlation between SMC4 expression and overall survival (OS) in TNBC patients with mesenchymal-stem like subtype disease, in the lower quartile (Figure 3; log rank p -value: 0.046 for overall survival, hazard ratio: 0.36 (0.13-1.02) (Fig. 3)). SMC4 mRNA levels were a positive prognostic indicator in patients with mesenchymal stem-like TNBC. Median OS was 21 months for mesenchymal stem-like TNBC patients with low tumor expression of SMC4 while median OS was 55.23 months for mesenchymal stem-like TNBC patients with high tumor expression of SMC4 (Chart 4).

We also observed a correlation between SMC4 expression and overall survival (OS) in TNBC patients with luminal androgen receptor subtype disease, in the lower quartile, which approached statistical significance (Figure 3; log rank p -value: 0.057 for overall survival, hazard ratio: 0.55 (0.3-1.03) (Fig. 3)). SMC4 mRNA levels were a positive prognostic indicator in patients with luminal androgen receptor TNBC. Median OS was 30.43 months for luminal androgen receptor TNBC patients with low tumor expression of SMC4 while median OS was 47.21 months for luminal androgen receptor TNBC patients with high tumor expression of SMC4 (Chart 4).

SMC4 primary tumor expression was not correlated with overall survival in the basal-like 1 subtype (Figure 3; log rank p -value: 0.12 for OS, hazard ratio: 0.54 (0.24-1.19) (Fig. 3), in the basal-like 2 subtype (Figure 3; log rank p -value: 0.56 for OS, hazard ratio: 0.73 (0.25-2.12) (Fig. 3), and in the immunomodulatory subtype (Figure 3; log rank p -value: 0.4 for OS, hazard ratio: 1.52 (0.57-4.04) (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 structural maintenance of chromosomes 4, encoded by the SMC4 gene, is a defining transcriptional feature of triple negative breast cancer. SMC4 was also differentially expressed in the bulk tumors of patients with early-onset breast cancer. Expression of SMC4 was correlated with overall survival in patients with basal-like subtype breast cancer, and within triple negative breast cancer patients, primary tumor expression of SMC4 was correlated with overall survival in patients with mesenchymal subtype disease. Structural maintenance of chromosomes 4 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: 90
Probe ID: 9527
p-value: 6.14E-13
t: -9.934696
B: 19.325964
Gene: SMC4
Gene name: structural maintenance of chromosomes 4

Chart 1: SMC4 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: 531
Probe ID: 2650199
p-value: 1.40E-10
t: -8.01
B: 13.919554
Gene: SMC4
Gene name: structural maintenance of chromosomes 4

Chart 2: SMC4 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: SMC4 is expressed at significantly higher levels in primary TNBC tumor cells as compared to normal cells of the breast.

The mRNA expression level of SMC4 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 SMC4 expression between normal cells of the breast and TNBC tumor cells, a p -value, listed above.

Figure 2: SMC4 expression correlates with overall survival in patients with basal-like breast cancer, but not in patients with luminal A, luminal B, HER2+, or normal-like subtype cancer.

Depicted in this Kaplan-Meier plot is the probability of overall survival (OS) 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 SMC4 in patient primary tumors. The log rank p -value denoting statistical significance of difference in overall 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 SMC4 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 SMC4 expression: 57.53 months

2 High SMC4 expression: 115 months

3 **Chart 3: Median overall survival is superior in basal-like subtype breast cancer patients with high**
4 **primary tumor expression of SMC4.**

5 The overall survival of $n=431$ basal-like subtype breast cancer patients based on stratification into low or
6 high tumor expression of SMC4 is listed in this chart.

Figure 3: SMC4 expression correlates with overall survival in triple negative breast cancer patients whose tumors are of the mesenchymal, mesenchymal stem-like, and luminal androgen receptor molecular subtype.

Depicted in this Kaplan-Meier plot is the probability of overall survival (OS) for $n=103$ patients with basal-like 1 subtype TNBC (upper left), $n=58$ patients with basal-like 2 subtype TNBC (upper right), $n=149$ patients with immunomodulatory subtype TNBC (middle left), $n=116$ patients with luminal androgen receptor subtype TNBC (middle right), $n=114$ 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 SMC4 in the primary tumors of patients with TNBC, in the lower quartile. The log rank p-value denoting statistical significance of difference in overall 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 SMC4 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.

Mesenchymal

Low SMC4 expression: 30.31 months

High SMC4 expression: 56.4 months

Mesenchymal stem-like

Low SMC4 expression: 21 months

High SMC4 expression: 55.23 months

Luminal androgen receptor

Low SMC4 expression: 30.43 months

High SMC4 expression: 47.21 months

Chart 4: In patients with mesenchymal, mesenchymal stem-like, and luminal androgen receptor subtype disease, median overall survival is superior in triple negative breast cancer patients with high primary tumor expression of SMC4.

The overall survival of $n=114$ mesenchymal subtype, $n=39$ mesenchymal stem-like subtype, and $n=116$ luminal androgen receptor subtype TNBC patients based on stratification into low or high tumor expression of SMC4 is listed in this chart, in the lower quartile.