Lactate Dehydrogenase B: A Metabolic Marker of Response to Neoadjuvant Chemotherapy in Breast Cancer

Jennifer B. Dennison¹, Jennifer R. Molina¹, Shreya Mitra¹, Ana M. González-Angulo¹,², Justin M. Balko⁴, María G. Kuba³, Melinda E. Sanders⁶,⁷, Joseph A. Pinto⁸, Henry L. Gómez⁹, Carlos L. Arteaga³,⁶,⁷, Robert E. Brown³, and Gordon B. Mills¹,²

Abstract

Purpose: Although breast cancers are known to be molecularly heterogeneous, their metabolic phenotype is less well-understood and may predict response to chemotherapy. This study aimed to evaluate metabolic genes as individual predictive biomarkers in breast cancer.

Experimental Design: mRNA microarray data from breast cancer cell lines were used to identify bimodal genes—those with highest potential for robust high/low classification in clinical assays. Metabolic function was evaluated in vitro for the highest scoring metabolic gene, lactate dehydrogenase B (LDHB). Its expression was associated with neoadjuvant chemotherapy response and relapse within clinical and PAM50-derived subtypes.

Results: LDHB was highly expressed in cell lines with glycolytic, basal-like phenotypes. Stable knockdown of LDHB in cell lines reduced glycolytic dependence, linking LDHB expression directly to metabolic function. Using patient datasets, LDHB was highly expressed in basal-like cancers and could predict basal-like subtype within clinical groups [OR = 21 for hormone receptor (HR)-positive/HER2-negative; OR = 10 for triple-negative]. Furthermore, high LDHB predicted pathologic complete response (pCR) to neoadjuvant chemotherapy for both HR-positive/HER2-negative (OR = 4.1, P < 0.001) and triple-negative (OR = 3.0, P = 0.003) cancers. For triple-negative tumors without pCR, high LDHB posttreatment also identified proliferative tumors with increased risk of recurrence (HR = 2.2, P = 0.006).

Conclusions: Expression of LDHB predicted response to neoadjuvant chemotherapy within clinical subtypes independently of standard prognostic markers and PAM50 subtyping. These observations support prospective clinical evaluation of LDHB as a predictive marker of response for patients with breast cancer receiving neoadjuvant chemotherapy.

Clin Cancer Res; 1–11. ©2013 AACR.

Introduction

Molecular subtyping of breast cancers has identified multiple gene clusters that can predict outcomes independently of clinical characteristics and the standard biomarkers: estrogen receptor (ER), progesterone receptor (PR), and human EGF receptor 2 (HER2; refs. 1, 2). Subtype gene signatures are often composed of different mRNAs but are highly correlated and can equally predict outcomes, reflecting fundamental biologic differences between breast cancer lineages (3, 4).

While able to provide clinically useful information for a subset of ER-positive, node-negative tumors (5, 6), mRNA profiling approaches such as Oncotype DX are limited by type and purity of the specimen. For instance, Oncotype DX and immunohistochemistry (IHC)/FISH scoring of HER2 may not agree if the stromal component of the tumor contaminates the mRNA pool (7, 8). Even with a relatively pure specimen, clinically useful results with Oncotype DX testing are not guaranteed; 37% of scored tumors are ‘intermediate’ without a treatment recommendation (9). In clinical research, mRNA profiling approaches can be problematic if tumors are necrotic or have a low concentration of malignant cells as often found in cancers pretreated with chemotherapy (10).

Additional predictive biomarkers, particularly for intermediate-grade or chemotherapy-resistant tumors, may complement existing mRNA profiling efforts for ER, HER2, and proliferation-related genes. We hypothesized that new
types of biomarkers could be discovered by exploring functional differences in metabolic pathways as these pathways may predict response to therapy.

While many cancers preferentially generate ATP via anaerobic glycolysis in the presence of oxygen, a process termed the “Warburg effect” (11), the metabolic phenotypes of breast cancers are heterogeneous; more than a 20-fold range in glucose uptake has been reported as quantified by \(^{18}\text{FDG-PET}\) maximum standard uptake values (12). To study metabolic differences between breast cancers and to avoid interference from the microenvironment, mRNA microarray data from breast cancer cell lines were used to identify breast cancers most likely to respond to neoadjuvant chemotherapy as well as those with the highest risk of relapse that may benefit from additional adjuvant therapy.
antibodies for LDHA (Cell Signaling; 3582S; 1:500) and LDHB (Abcam; ab85319; 1:2,000) and secondary antibodies, antirabbit or antimouse immunoglobulin G (IgG) horseradish peroxidase–linked secondary antibody (Cell Signaling Technology; 1:2,000), were as described previously (19).

The oxygen consumption rates (OCR) and the extracellular acidification rates (ECAR) of cell lines were quantified using the Seahorse Extracellular Flux Analyzer (XF96, Seahorse Biosciences). For adherent lines, at least 5 wells for each cell line were seeded on XF 96-well microplates (Seahorse Biosciences), 0.6 × 10^5 to 1.6 × 10^5 cells/well in 5% FBS DMEM, and left overnight to attach. Approximately 1 hour before the Seahorse readings, the medium was replaced with exchange medium: serum-free, bicarbonate-free DMEM with phenol red (5 mmol/L glucose, 0.5 glutamine, 1 mmol/L sodium lactate). For suspension cell lines, wells were pretreated with CellTak (BD Biosciences) per the manufacturer instructions, and 1.6 × 10^5 cells were added to the wells in the exchange medium on the day of the readings. OCR and ECAR readings were determined for 6 cycles (2-minute mixing, 5-minute measuring), and the baseline measurements were the average of the last 3 readings before oligomycin addition (1 μg/mL final concentration). The absolute OCR reduction after oligomycin addition was defined at the ATP-dependent OCR (OCRATP).

Analytical and statistical methods

Publically available mRNA microarray data from a panel of breast cancer cell lines (20) were used to identify bimodal genes based on KEGG function from central carbon metabolic pathways. For probe sets with at least a 10-fold range, R code (web site http://bioinformatics.mdanderson.org/Software/OOMPA) was used to compute the bimodality index as previously described (13). A probe set was considered bimodal if the bimodality index was >1.1, and the proportion of samples in one group was >10%. Bimodal genes were selected on the basis of their KEGG function including genes from central carbon metabolic pathways (21).

mRNA and protein expression differences between groups of breast cancers and cell lines were assessed using t tests and one-way ANOVA. Survival curves were estimated using the Kaplan–Meier method, and differences were evaluated using the log-rank test or univariate Cox regression. Fisher exact test for single variables and binary logistical regression for multiple variables were used to determine the impact of potential markers on pCR. Statistical analyses were conducted using Prism 5.0c (GraphPad Software) or SPSS Statistics (Version 19.0, SPSS). P < 0.05 (2-sided) was considered significant.

Results

Identification of LDHB as a bimodal metabolism gene

Using mRNA microarray data from a panel of breast cancer cell lines, metabolism-related genes were ranked by their bimodality index values (Supplementary Table S3). As compared with clinical markers ERBB2 and ESR1, 20 metabolism-related genes with similar bimodality were identified including the highest-ranked gene, LDHB (Fig. 1A and B). LDHB expression was the highest in basal-like or triple-negative lines. mRNA microarray expression of LDHB separated by HER2 and ER status of cell lines. Lines represent the median values. D, LDHB protein levels were differentially expressed in cell lines as shown by Western blotting of LDHA and LDHB in a panel of cell lines including HER2-amplified, luminal, and basal-like subtypes as defined previously (20). Twenty micrograms of protein was loaded per lane. *, P < 0.05; ***, P < 0.001.
LDHB form active tetrameric enzymes with each other, the relative expression levels of mRNA and protein were evaluated for both subunits (Fig. 1B and D). Consistent with the mRNA data (Fig. 1B) and a recent study (22), differential protein expression of LDHB but not LDHA was confirmed by Western blotting (Fig. 1D).

While LDHA was generally high, LDHB when present contributed substantially to the total lactate dehydrogenase activity in the cell lines (>50% for HCC1187, HCC1937, and MDAMB175; Supplementary Fig. S2). Certain basal A cell lines like BT20 and MDAMB468 did not express LDHB, but LDHB was highly expressed in basal B lines which include the stem cell–like, claudin-low subset of breast cancers (refs. 23,24; Supplementary Fig. S2). Within the ER-positive/HER2-negative lines, LDHB was expressed in a minority of cell lines, typically those with lower ESR1 mRNA levels (LDHB vs. ESR1: Pearson r = 0.58, P = 0.04).

Glycolytic phenotyping of breast cancer cell lines and role of LDHB

To determine how LDHB expression is related to metabolic state, the rates of oxygen consumption (OCR) and extracellular acidification (ECAR) were quantified using a panel of cell lines (n = 19) with representatives from each of the known subtypes (20). The ratios of the ATP-synthase dependent OCR in the mitochondria (OCR_{ATP}) and the ECAR (a measure of lactate production rates) were used to rank order the cell lines (Fig. 2A and B). Consistent with previous reports of high 18FDG-PET uptake in basal-like tumors (12), the metabolic phenotypes as determined by OCR_{ATP}/ECAR ratios of breast cancer cell lines were highly variable (20-fold range) and most glycolytic in basal-like as compared with luminal-like cells (Fig. 2B, P = 0.01). Importantly, LDHB was equally predictive of metabolic phenotype with the highest expression in the most glycolytic lines (Fig. 2B, P = 0.005).

To evaluate the functional metabolic role of LDHB, we created 2 sets of isogenic cell lines with stable knockdowns of LDHA or LDHB using breast cancer cells with high LDHB in the parental lines (Supplementary Fig. S3). Knockdown of LDHA or LDHB promoted a more oxidative metabolic state as shown by increased OCR_{ATP}/ECAR ratios for both cell lines (Fig. 2C). The changes were primarily attributable to increased OCR_{ATP} (Supplementary Fig. S3) and...
consistent with previous reports of mitochondrial compensation after stable knockdown of LDHA (25).

**Expression of LDHB is sufficient to predict basal phenotype**

To determine whether the cell line data translated to primary tumors, the mRNA expression of *LDHB* was evaluated using multiple cohorts of patients’ cancers. As expected on the basis of the cell line data and a recent report (22), basal-like breast cancers as defined by PAM50 expressed higher levels of *LDHB* in multiple datasets (Fig. 3A; Supplementary Fig. S4). Using standard clinical markers, *LDHB* was also higher in triple-negative breast cancers and the lowest in HR-positive/HER2-negative cancers (Fig. 3B; Supplementary Fig. S5). In contrast, *LDHA* was not differentially expressed in the breast cancer subtypes (data not shown) in agreement with a previous report (26).

Clinical classification of breast cancers by ER/PR/HER2 status did not exclusively define PAM50 intrinsic subtype in our cohorts; 17% to 28% of triple-negative tumors were not basal-like, and 31% to 38% of HR-positive/HER2-negative tumors were not luminal-like (Table 1). Thus, we evaluated

---

**Figure 3.** *LDHB* mRNA was highly expressed in basal-like and triple-negative disease and predicted basal-like subtyping of breast cancers independently of HR-status. *LDHB* mRNA expression separated by (A) PAM50 intrinsic subtype and (B) clinical ER/HER2 status (TCGA, Supplementary Table S1). The box and whiskers plots (A and B) show the minimum and maximum values. Forest plots for *LDHB* prediction of basal-like phenotype by cohort for (C) HR-positive/HER2-negative and (D) triple-negative breast cancers. Marker size represents the size of the cohort, and the bars cover the 95% CI. Results from a triple-negative TMA stained for LDHB (Fig. 4) are also plotted (D) but are not part of the average. HR, hormone receptor (ER and/or PR); TN, triple-negative. ***, P < 0.001.
the ability of LDHB to predict intrinsic subtype within HR-positive/HER2-negative and triple-negative cancers. LDHB was highly associated with basal-like phenotype independently of HR status (Supplementary Figs. S6 and S7). The threshold for high/low expression of LDHB was determined by optimizing the ORs of the MAQC cohort based on the separation of basal-like subtype within the HR-positive/HER2-negative group (0.60, Supplementary Fig. S6). Using this threshold for all remaining cohorts, LDHB was able to predict basal-like subtype within the HR-positive/HER2-negative and triple-negative breast cancer groups with a high degree of power (Fig. 3C and D). The ORs for prediction of basal phenotype was overall lower for triple-negative as compared with the HR-positive/HER-negative cancers. However, this trend was not observed for the TCGA cohorts; LDHB levels were as predictive of basal phenotype for the triple-negative group as compared with the HR-positive/HER2-negative group (Fig. 3C and D), perhaps reflecting the higher purity of the TCGA specimens and consequently a reduced number of normal-like breast cancers (27). In fact, exclusion of the normal-like breast cancers in the other cohorts increased the ORs for basal prediction within the triple-negative groups (data not shown).

**LDHB predicts response to neoadjuvant chemotherapy**

Given that pCR after neoadjuvant chemotherapy predicts reduced risk of relapse independently of clinical subtype in breast cancer (28), pCR was used to evaluate LDHB as a biomarker of response. The ability of LDHB to predict pCR after neoadjuvant chemotherapy was evaluated in 2 independent cohorts (MAQC and MDACCSS).

First, the HR-positive/HER2-negative groups were evaluated for differences in pCR using the LDHB threshold determined from the basal-like prediction (0.60, Fig. 3C). High nuclear grade, basal-like subtyping, and high LDHB predicted pCR to neoadjuvant chemotherapy by univariate analyses for 2 independent cohorts (Table 1) and in the combined cohort [OR, 4.1; 95% confidence interval (CI),

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>MAQC HR+/HER2-neg</th>
<th>MAQC Triple-negative</th>
<th>MDACCSS HR+/HER2-neg</th>
<th>MDACCSS Triple-negative</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of patients</td>
<td>137</td>
<td>68</td>
<td>167</td>
<td>111</td>
</tr>
<tr>
<td>Age, y</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;50</td>
<td>62</td>
<td>30</td>
<td>88</td>
<td>63</td>
</tr>
<tr>
<td>&gt;50</td>
<td>75</td>
<td>37</td>
<td>79</td>
<td>48</td>
</tr>
<tr>
<td>Tumor size at diagnosis (TNM)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T0/T1/T2</td>
<td>94</td>
<td>38</td>
<td>86</td>
<td>50</td>
</tr>
<tr>
<td>T3/T4</td>
<td>43</td>
<td>29</td>
<td>81</td>
<td>61</td>
</tr>
<tr>
<td>Lymph node node</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Negative</td>
<td>48</td>
<td>11</td>
<td>62</td>
<td>28</td>
</tr>
<tr>
<td>Positive</td>
<td>89</td>
<td>56</td>
<td>105</td>
<td>83</td>
</tr>
<tr>
<td>Modified Black's nuclear grade</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1–2</td>
<td>90</td>
<td>11</td>
<td>84</td>
<td>14</td>
</tr>
<tr>
<td>3</td>
<td>45</td>
<td>50</td>
<td>71</td>
<td>82</td>
</tr>
<tr>
<td>Unknown or indeterminate</td>
<td>2</td>
<td>7</td>
<td>12</td>
<td>15</td>
</tr>
<tr>
<td>PAM50 intrinsic subtype</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Luminal A</td>
<td>52</td>
<td>0</td>
<td>73</td>
<td>0</td>
</tr>
<tr>
<td>Luminal B</td>
<td>33</td>
<td>4</td>
<td>42</td>
<td>0</td>
</tr>
<tr>
<td>HER2-enriched</td>
<td>1</td>
<td>0</td>
<td>11</td>
<td>8</td>
</tr>
<tr>
<td>Normal</td>
<td>37</td>
<td>15</td>
<td>15</td>
<td>9</td>
</tr>
<tr>
<td>Basal</td>
<td>14</td>
<td>49</td>
<td>26</td>
<td>92</td>
</tr>
<tr>
<td>LDHB (0.60 threshold)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>94</td>
<td>18</td>
<td>126</td>
<td>32</td>
</tr>
<tr>
<td>High</td>
<td>43</td>
<td>50</td>
<td>41</td>
<td>80</td>
</tr>
<tr>
<td>LDHB (0.94 threshold)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>106</td>
<td>24</td>
<td>134</td>
<td>40</td>
</tr>
<tr>
<td>High</td>
<td>31</td>
<td>44</td>
<td>33</td>
<td>71</td>
</tr>
</tbody>
</table>

**NOTE:** P was calculated by Fisher exact test. For PAM50 intrinsic subtyping, basal-like subtype was compared with other subtypes pooled (luminal A, luminal B, HER2-enriched, and normal-like).
2.0–8.3; \( P < 0.001 \) for high LDHB]. In a logistic regression model for the combined cohorts with these characteristics as predictors, only LDHB and nuclear grade remained significant (Table 2).

For triple-negative cancers, adjustment of LDHB threshold from 0.60 to 0.94 optimized the ability of LDHB to predict pCR in the MDACCSS cohort (approaching statistical significance, \( P = 0.087 \), Table 1). Using this threshold, LDHB predicted pCR in the MAQC cohort (threshold = 0.020) and in the combined cohort (OR, 1.4–6.2; \( P = 0.003 \)). Although the basal-like subtype predicted pCR in the MAQC cohort by univariate analysis, only LDHB and tumor size were significant in a multivariate logistic regression model of the combined cohort (Table 2). Interestingly, LDHB was highly expressed in the most aggressive triple-negative cancers within the basal-like subtype as shown by its association with the proliferation marker CCNB1 (Supplementary Fig. S8). Therefore, an adjustment of the LDHB threshold may allow stratification within basal-like cancers.

**LDHB expression in triple-negative breast cancers with residual disease**

To further evaluate the potential predictive role of LDHB, an independent sample set of relatively advanced-stage, triple-negative disease (primarily stage III, Supplementary Table S2) biopsied after neoadjuvant chemotherapy was quantified for LDHB protein expression by IHC. As expected on the basis of the cell line data (Fig. 1), intertumoral expression of LDHB was heterogeneous in the breast cancer cells (Fig. 4A). Interestingly, LDHB expression was generally ubiquitous in the tumor microenvironment, which may, in part, explain why differential expression of LDH isoforms was not previously detected in breast cancer (29). Consistent with mRNA microarray data of patient tumors, high LDHB was also able to predict basal-like phenotype [threshold = 180 for lowest \( P \); sensitivity = 96% (47 of 49); specificity = 60% (18 of 30); Figs. 3D and 4C]. Using the same LDHB intensity threshold as the basal-like prediction analysis, LDHB was the only predictive marker for relapse in this cohort (Fig. 4B; Supplementary Table S2).

High LDHB marked the most aggressive disease that was more common in young women as shown by association of LDHB with Ki67 and age (Fig. 4D). Cancers with low LDHB were also more likely to have high AR and HER2 (Fig. 4D).

**Discussion**

Molecular profiling methods in breast cancer used for prognosis and to predict lack of benefit from chemotherapy such as Oncotype DX and PAM50 primarily focus on HER2, ER, and proliferation-related genes (9,14). Here, we evaluate another functional hallmark of cancer, deregulation of cellular energetics (30). By starting with mRNA microarray data of cell lines, bimodal genes within metabolic pathways

---

**Table 2.** Binary logistical regression for odds of pCR after neoadjuvant chemotherapy by HR status, combined MAQC and MDACCSS cohorts

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>HR-positive/HER2-negative</th>
<th></th>
<th></th>
<th>Triple-negative</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>OR (95% CI)</td>
<td>( P )</td>
<td>OR (95% CI)</td>
<td>( P )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tumor size at diagnosis (TNM)</td>
<td></td>
<td></td>
<td>0.017</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T0/T1/T2</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T3/T4</td>
<td></td>
<td></td>
<td>0.44 (0.23–0.87)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modified Black’s nuclear grade</td>
<td></td>
<td>0.001</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1–2</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>4.30 (1.78–10.42)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PAM50 intrinsic subtype</td>
<td></td>
<td>0.580</td>
<td>0.898</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Luminal A</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Luminal B</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HER2-enriched</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normal</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basal</td>
<td>1.32 (0.49–3.58)</td>
<td>0.018</td>
<td>1.06 (0.42–2.61)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LDHB (0.60 threshold)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High</td>
<td>2.86 (1.19–6.84)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LDHB (0.94 threshold)</td>
<td></td>
<td></td>
<td>0.004</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High</td>
<td>3.18 (1.45–6.99)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**NOTE:** Characteristics were included in the models if \( P \leq 0.05 \) by univariate analysis in at least one cohort (Table 1) or the combined cohort. Cases were excluded if all characteristics were not reported. The ORs were not statistically significant if basal-like and luminal B cases were considered as one group. Values in bold were statistically significant.
were detected in the cancer cells without influence or dilution by the tumor microenvironment. This approach led to the evaluation of LDHB as a putative biomarker, which proved to be highly expressed in aggressive, glycolytic breast cancers primarily of the basal subtype.

Bimodal expression of LDHB may have clinical relevance because cancers with high LDHB were most responsive to neoadjuvant chemotherapy independently of established prognostic factors (grade, tumor size) and molecular markers (HR status and PAM50 subtyping). Although it might be expected that higher response rates to neoadjuvant chemotherapy would lead to reduced rates of relapse, high LDHB tumors without pCR post-neoadjuvant chemotherapy were also more likely to relapse in our triple-negative cohort. One possible explanation is that LDHB marks cancers with higher metastatic potential leading to more residual micrometastases. Also, LDHB is reported to facilitate tumor growth in basal-like breast cancers (22), so faster rates of relapse are consistent with higher rates of proliferation as shown by association with Ki67 and proliferation markers in high LDHB cancers. However, LDHB not Ki67 predicted relapse in our triple-negative cohort supporting the hypothesis that LDHB is more than a surrogate proliferation marker.

We showed that LDHB expression levels in breast cancers were bimodal, an important characteristic for a robust biomarker. The most striking observation was the near total depletion of LDHB in many samples. For breast cancer cell lines with low LDHB levels, the contribution of LDHA to the total LDH activity was almost 100%. Likewise, in most luminal tumors, LDHB was highly expressed in the tumor microenvironment but not detected in cancer cells (Fig. 4).
In contrast, LDHB levels were high in many basal-like cancer cells, in some cell lines exceeding that of LDHA. To determine whether overexpression was regulated at the gene level, we evaluated copy number gain for LDHB at chromosome 12p12, the same amplicon as KRAS. While we did see gain in approximately 40% of TCGA basal-like tumors that correlated with mRNA expression, the differences in mRNA expression of LDHB between luminal and basal cancers were independent of gene copy number (Supplementary Fig. S9). This observation for breast cancer is in contrast to that of lung cancer; LDHB was recently shown to be highly expressed in lung adenocarcinomas with KRAS amplification or mutations (31). Recently reported for breast cancer (32) and similar to regulation of LDHB in prostate cancer (33), DNA hypermethylation of LDHB may contribute to low expression of LDHB mRNA in luminal breast cancer (Supplementary Fig. S9).

While LDHB expression levels were associated with breast cancer subtype as defined by PAM50, high LDHB identified aggressive cancers were predominantly but not exclusively basal-like (Fig. 4). Importantly, as compared with basal-like phenotype, LDHB was a more robust predictor of response to neoadjuvant chemotherapy (Table 2). Our TMA of triple-negative breast cancers with matched PAM50 subtyping also showed that LDHB was highly expressed not only in basal but also in a subset of HER2-enriched and luminal B cancers with increased rates of relapse (Fig. 4). Consistent with these findings, another study reported that only basal-like, HER2-enriched, and luminal B cancers with the worst clinical outcomes were able to form stable grafts in mice (34); importantly, we determined that 11 of the 12 stable grafts (of 49 tumors transplanted) expressed high levels of LDHB (GSE32532, data not shown). On the basis of these results, we anticipate that LDHB expression may provide additional information beyond the standard proliferation and hormone markers used in molecular profiling tests like Onco-type DX and PAM50. However, additional studies will be required to understand the prognostic or predictive value of LDHB expression as compared to other molecular classifiers and signatures for breast cancer.

LDHB expression is likely to also provide information on the metabolic phenotype of breast cancers that could contribute to selection of new treatment modalities. High LDHB marked the most glycolytic breast cancer cells, often basal-like, within the HR-positive/HER2-negative and triple-negative groups. Our cell line studies showed a direct effect and strong positive association with LDHB and glycolytic phenotype (Fig. 2). Consistent with 18FDG-PET reports (12, 35), cell lines with a more glycolytic phenotype in our study were primarily basal-like: those with genetic instability or increased proliferation often caused by loss of TP53, MYC amplification, or BRCA1 mutations. High glycolytic flux may provide these types of cancers a survival advantage because the Warburg effect allows more rapid consumption of glucose and consequently can support increased rates of proliferation, regardless of tumor oxygenation (15). This adaptation may be less important for luminal-like cancers whose survival may be more dependent on antiapoptotic mechanisms such as Bcl-2 expression (36).

Although the general enzymatic function of LDHB is known, the functional role of LDHB is cell type and context dependent. In tissues like the brain that use lactate as energy source, LDHB promotes lactate uptake during exercise; other cells like erythrocytes use LDHB for glycolysis to synthesize lactate (37). While LDHB is thought to convert lactate to pyruvate in certain tissues, our breast cancer cell line results show that LDHB is functionally similar to LDHA and contributes to the conversion of pyruvate to lactate (Fig. 2). We propose that LDHB is constitutively expressed in most basal-like breast cancers and significantly contributes to the overall LDH activity. Consequently, inhibition of LDHA, a proposed therapeutic target in breast cancer (25, 38), would have less effect on the total lactate dehydrogenase activity if LDHB were coexpressed. Indeed, high LDHB expression may identify tumors less likely to respond to LDHA inhibitors.

While the function of LDHB is consistent with an increased glycolytic phenotype, LDHB expression was insufficient to completely explain the metabolic variability between breast cancer cell lines (Fig. 1B). LDHB is likely part of a network of metabolic proteins that together create a specific glycolytic phenotype. Low expression of fructose-1,6-bisphosphatase 1 (FBP1) and high expression of monocarboxylic acid transporter 1 (SLC16A1) and glutaminase (GLS), previously reported for basal-like phenotype (39, 40), were associated with high LDHB (data not shown). We propose that LDHB expression may mark a particular lineage or state of differentiation with altered metabolic demands. Consistent with this hypothesis, LDH isoform distribution is well-known to be a fundamental property of cell type and developmental stage (41). Also, low LDHB in HER2-positive and luminal-like cancers is consistent with a model of breast cancer lineage (42), from least to most differentiated (LDHB levels; claudin-low/basal > HER2 > luminal). Given that LDHB mRNA levels were unchanged by chemotherapy in breast cancer (GSE28844, n = 28 pairs, data not shown), LDHB expression appears to be a property of lineage and independent of the tumor microenvironment.

In conclusion, LDHB expression in breast cancer cells was bimodal, a desirable property for a clinical biomarker. As expected on the basis of its enzymatic function, high LDHB was associated with glycolytic, basal-like phenotype. While additional prospective studies are required, LDHB in our cohorts was an independent predictive marker of pCR for HER2-negative cancers (HR-positive or HR-negative) and relapse in triple-negative disease.

Disclosure of Potential Conflicts of Interest

G.B. Mills has a commercial research grant from AstraZeneca, Celgene, Genentech, Exelixis/Sanoft, GSK, Roche, Wyeth Research, and Pfizer/Puma; has ownership interest (including patents) from Catena Pharmaceuticals, PTIV Ventures, and Spindle Top Ventures; and is a consultant/advisory board member of AstraZeneca, Catena Pharmaceuticals, Taux Therapeutics, Critical Outcome Technologies, Daiichi Pharm., Targeted Molecular Diagnostics LLC, Foundation Medicine, HanAll Bio Pharm Korea, Komen Foundation, Novartis, and Sypmogen. No potential conflicts of interest were disclosed by the other authors.
Authors' Contributions

Conception and design: J.B. Dennison, A. González-Angulo, R.E. Brown

Acquisition of data (provided animals, acquired and managed patients, provided facilities, etc.): J.B. Dennison, J.R. Molina, S. Mitra, A. González-Angulo, J.M. Balko, M.G. Kuba, M.E. Sanders, J.A. Pinto, H.L. Gomez, C.L. Arteaga, R.E. Brown, G.B. Mills

Analysis and interpretation of data (e.g., statistical analysis, biostatistics, computational analysis): J.B. Dennison, A. González-Angulo, J.M. Balko, M.E. Sanders, R.E. Brown, G.B. Mills

Writing, review, and/or revision of the manuscript: J.B. Dennison, J.R. Molina, S. Mitra, A. González-Angulo, M.E. Sanders, J.A. Pinto, H.L. Gomez, R.E. Brown, G.B. Mills

Administrative, technical, or material support (i.e., reporting or organizing data, constructing databases): J.M. Balko, M.E. Sanders, J.A. Pinto, H.L. Gomez, C.L. Arteaga

Acknowledgments

The authors thank Pamela K. Johnston for help with the immunohistochemical assay for LDHB, Ju- Seog Lee and Fan Zhang for assistance with patient datasets, and Xiudong Lei for suggestions on the biostatistical analyses.

Grant Support

This work was supported by the Susan G. Komen Foundation (KG081694), GlaxoSmithKline, Vanderbilt Breast Cancer Special Program of Research Excellence (SPORE, P50CA98131), American Cancer Society Clinical Research Professorship Grant (CRPF-07-234) Entertainment Industry Foundation, and Susan G. Komen for the Cure Scientific Advisory Council Grant (SAC100013). S. Mitra is supported by a Susan G. Komen Postdoctoral Fellowship. J.B. Dennison is supported by a GlaxoSmithKline TRIUMPH post-doctoral fellowship and the American Cancer Society, Joe and Jesse Crump Medical Research Fund Postdoctoral Fellowship.

The costs of publication of this article were defrayed in part by the payment of page charges. This article must therefore be hereby marked advertisement in accordance with 18 U.S.C. Section 1734 solely to indicate this fact.

Received March 5, 2013; revised May 13, 2013; accepted May 15, 2013; published OnlineFirst May 22, 2013.

References

# Lactate Dehydrogenase B: A Metabolic Marker of Response to Neoadjuvant Chemotherapy in Breast Cancer


*Clin Cancer Res*  Published OnlineFirst May 22, 2013.

<table>
<thead>
<tr>
<th>Updated version</th>
<th>Access the most recent version of this article at: doi:<a href="http://10.1158/1078-0432.CCR-13-0623">10.1158/1078-0432.CCR-13-0623</a></th>
</tr>
</thead>
<tbody>
<tr>
<td>Supplementary Material</td>
<td>Access the most recent supplemental material at: <a href="http://clincancerres.aacrjournals.org/content/suppl/2013/05/22/1078-0432.CCR-13-0623.DC1">http://clincancerres.aacrjournals.org/content/suppl/2013/05/22/1078-0432.CCR-13-0623.DC1</a></td>
</tr>
</tbody>
</table>

**E-mail alerts**  
Sign up to receive free email-alerts related to this article or journal.

**Reprints and Subscriptions**  
To order reprints of this article or to subscribe to the journal, contact the AACR Publications Department at pubs@aacr.org.

**Permissions**  
To request permission to re-use all or part of this article, contact the AACR Publications Department at permissions@aacr.org.