

Identification of a claudin-4 and E-cadherin score to predict prognosis in breast cancer

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The elevated expression of claudins (CLDN) and E-cadherin (CDH-1) was found to correlate with poor prognostic features. Our aim was to perform a comprehensive analysis to assess their potential to predict prognosis in breast cancer. The expression of CLDN-1, -3-5, -7, -8, -10, -15, -18, and E-cadherin at the mRNA level was evaluated in correlation with survival in datasets containing expression measurements of 1809 breast cancer patients. The breast cancer tissues of 197 patients were evaluated with tissue microarray technique and immunohistochemical method for CLDN-1-5, -7, and E-cadherin protein expression. An additional validation set of 387 patients was used to test the accuracy of the resulting prognostic score. Based on the bioinformatic screening of publicly-available datasets, the metagene of CLDN-3, -4, -7, and E-cadherin was shown to have the most powerful predictive power in the survival analyses. An immunohistochemical protein profile consisting of CLDN-2, -4, and E-cadherin was able to predict outcome in the most effective manner in the training set. Combining the overlapping members of the above two methods resulted in the claudin-4 and E-cadherin score (CURIO), which was able to accurately predict relapse-free survival in the validation cohort ($P = 0.029$). The multivariate analysis, including clinicopathological variables and the CURIO, showed that the latter kept its predictive power ($P = 0.040$). Furthermore, the CURIO was able to further refine prognosis, separating good versus poor prognosis subgroups in luminal A, luminal B, and triple-negative breast cancer intrinsic subtypes. In breast cancer, the CURIO provides additional prognostic information besides the routinely utilized diagnostic approaches and factors. (*Cancer Sci*, doi: 10.1111/j.1349-7006.2011.02085.x, 2011)

Investigation of the expression of tight junction molecules has recently gained increased importance due to its implicated prognostic value in breast cancer.^(1,2) The recently-identified new subtypes, named “claudin-low” breast carcinomas, propose a new challenge for the breast cancer research community due to their rarity. This subgroup typically exhibits high histological grade, with stem cell and epithelial-to-mesenchymal transition features, low expression of cell–cell junction proteins, and probably poor response to systemic therapy.^(3,4)

E-cadherin (CDH-1), a transmembrane protein that functions in epithelial cell–cell interactions as part of adherent junctions, is linking the membrane to the cytoskeletal matrix through interactions with α - and β -catenin. It is used in routine diagnostic pathology to distinguish lobular and ductal carcinomas.⁽⁵⁾ Studies evaluating the expression of E-cadherin report the loss of these molecules in approximately 80% of lobular carcinomas.⁽⁶⁻¹⁰⁾

Claudin (CLDN) tight junction molecules were originally described by Furuse *et al.* in 1998.⁽¹¹⁾ In the past decade, there have been multiple attempts to evaluate their expression in several pathological states and organs.⁽¹²⁾ In 36 of 39 invasive

breast cancer samples that we reported on in an earlier study, there was either an absence or scattered presence of the CLDN-1 protein.⁽¹³⁾ Claudin-1 expression also correlated with recurrence status and malignant potential in another study.⁽¹⁴⁾ A decreased level of CLDN-4 expression was observed in the majority of grade 1 invasive ductal carcinomas (IDC).⁽¹⁵⁾ Furthermore, CLDN-4 expression was significantly higher in basal-like breast carcinomas.⁽¹⁶⁾ The loss of CLDN-7 was found to correlate with histological grade in both ductal carcinoma *in situ* and IDC, and its expression was lost in the majority of lobular carcinoma *in situ* cases.⁽¹⁷⁾ The reduced expression of CLDN-7 correlated not only with higher tumor grade, but also with the metastatic states, including loco-regional recurrences.⁽¹⁸⁾ Reduced CLDN-16 expression was also described in metastatic breast tumors.⁽¹⁹⁾

Alterations in intercellular junctions and membrane proteins might lie behind some morphological and invasive properties of carcinomas. The changes of E-cadherin, CLDN-1, -4, and -7 expressions with their prognostic value and the recently-established intrinsic claudin-low subtype together underline the importance of the role of tight junction molecules in neoplastic transformation and the prognosis of breast cancer. Therefore, a systematic analysis of junctional protein families (CLDN and also cadherins) might be of prominent relevance. In the present study, we identified tight junction family molecules capable of acting as prognostic biomarkers in breast cancer.

Materials and Methods

Breast cancer datasets. An *in silico* analysis of publicly-available microarray data from 13 datasets was performed in the first line.⁽²⁰⁻³²⁾ The refined and established database was based on the gene expression data (Affymetrix human genome unigene [HGU]133A and HGU133 + 2 microarrays only), and survival information of 1809 patients downloaded from gene expression omnibus (GEO) (Table 1).⁽³³⁾ The expression data of *CDH-1*, *CLDN-1*, -3-11, and -14-18 were analyzed. All available probes were used for the analysis, excluding those that were not reliable across datasets (average expression <100, and maximal expression <500 of micro array suite [MAS]-5-normalized value). The signature containing the average score for all of the abovementioned CLDN and E-cadherin expression data was assigned as the complex junctional signature (CJS).

Breast cancer samples. The study was approved by the Institutional Review Board of Semmelweis University (Budapest, Hungary).

A training cohort of 197 selected breast carcinomas diagnosed between 1982 and 2007 with known relapse, and cases with no recurrence of disease on long-term follow-up, was

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Table 1. Clinicopathological characteristics of the patients and tumor samples used in the study

Cohort		Datasets	Training	Validation
Patients	<i>n</i>	1809	197	387
Age	Years ± SD	57 ± 13	60 ± 15	59 ± 13
Follow-up time	Months ± SD	123 ± 82	111 ± 12	102 ± 9
Relapse events	<i>n</i> (%)	689 (38.1%)	97 (49.2%)	153 (39.5%)
Histological type	IDC	0	118 (47.3%)	165 (65.8%)
	ILC	0	77 (30.9%)	27 (15.4%)
	Other	0	54 (21.6%)	46 (18.6%)
	Unknown	1809	0	0
Grade	1	98 (5.4%)	56 (22.4%)	181 (22.4%)
	2	534 (29.5%)	122 (48.9%)	145 (48.9%)
	3	312 (17.2%)	71 (28.5%)	91 (28.5%)
	Unknown	865 (52.1%)	0	0
Subtype	ER positive	968 (53.5%)	139 (70.5%)	319 (82.4%)
	ER negative	578 (31.9%)	58 (29.4%)	67 (17.3%)
	Unknown	263 (14.5%)	0	0

ER, estrogen receptor; IDC, invasive ductal carcinoma; ILC, invasive lobular carcinoma; SD, standard deviation.

set up (Table 1). Selected cases of formalin-fixed and paraffin-embedded (FFPE) tissues underwent histological re-examination, and regions of interests were marked for core punching. According to the diagnostic reports, which interpreted the immunophenotype as a surrogate of the molecular subtype, there were 98 luminal A, 41 luminal B, 20 HER-2-positive, and 38 triple-negative breast cancer (TNBC) tumors (Fig. S1). The expression of CLDN-1–5, -7, and E-cadherin proteins were evaluated by immunohistochemistry (IHC).

The validation cohort consisted of 387 unselected breast cancer samples diagnosed between 1999 and 2002 (Table 1). Of these, 148 (38.2%) received anthracycline- or taxane-based chemotherapy, and 101 additionally received irradiation (68.2%). Of the remaining 239 patients undergoing surgical resection without chemotherapy, 112 (46.8%) received radiotherapy. Recurrence-free survival curves according to histological type, grade, and molecular subtype are shown in Figure S1. The samples were analyzed for CLDN-4 and E-cadherin protein expression in the same fashion as the training set.

The tumors were previously classified during routine pathological examination into luminal A (estrogen receptor [ER]- and progesterone receptor [PgR]-expressing tumors with <20% Ki67 index and epidermal growth factor receptor-2 [HER-2] negativity), luminal B (ER- or PgR- and HER-2-expressing tumors, and ER- and PgR-expressing carcinomas with more than 20% Ki67 index), HER-2 (ER- and PgR-negative and HER-2 expression of 3+ at IHC or amplified by FISH evaluation when the IHC score was 2+), and TNBC (no expression of ER, PgR, or HER-2, nor amplification of the latter with FISH) groups.⁽³⁴⁾

Tissue microarray construction. Tissue microarray constructions (TMA) of all FFPE tumors were composed with the TMA builder instrument (Histopathology, Pécs, Hungary). The cores were 2 mm, in diameter and all the samples were investigated in duplicates.

Immunohistochemistry. The IHC reactions were performed on 4 µm-thick sections obtained from the TMA blocks. After deparaffinization, the slides were heated in a microwave oven in target retrieval solution (DAKO, Carpinteria, CA, USA) for 30 min. The automated Ventana ES immunostainer system was used according to the protocol provided by the manufacturer (Ventana Medical Systems, Tucson, AZ, USA). The E-cadherin and CLDN antibodies were used as follows: CLDN-1 (cat. no. 18-7362; Zymed, South San Francisco, CA, USA) at 1:80, -2 (cat. no. 18-7363; Zymed) at 1:80, -3 (cat. no. 34-1700; Zymed) at 1:80, -4 (cat. no. 18-7341; Zymed) at 1:100, -5 (cat. no. 18-7364; Zymed) at 1:120, -7 (cat. no. 34-9100; Zymed) at 1:100,

and E-cadherin (cat. no. M3612; DAKO) at 1:100. The tissues were counterstained with Mayer's hemalaun (00-8011; Zymed). Positive controls and negative control tissues were applied in all IHC runs.

Immunohistochemistry evaluation. The immunohistochemical reactions were considered positive when the CLDN (except CLDN-2, which was granular cytoplasmic, predominantly sub-membranous) and E-cadherin were expressed at the cell membranes (Fig. S2). Claudin-5 was not only expressed in the tumor cells, but in the endothelial cells as well. The stained slides were digitalized with a slide scanner (Mirax Scan; 3DHitech, Budapest, Hungary), and the intensity of the reaction (0, negative reaction; +1, weak positivity; +2, moderate positivity; and +3, strong reaction) and the frequency of positive cells (1, 0–5%; 2, >5–10%; 3, >10–20%; 4, >20–33%; 5, >33–50%; 6, >50–66%; 7, >66–80%; and 8, >80–100%) were integrated into a scoring system using TMA module software (version 11.49; 3DHitech) resulting in a numerical variable (range: 0–11) consisting of the sum of the intensity and frequency scores above. The indices were created from the arithmetic means of the respective CLDN and E-cadherin.

Statistics. The analyses for the datasets were performed in the R statistical environment (R version 2.10.1; R Foundation for Statistical Computing, Vienna, Austria) using the prediction analysis of microarrays (PAM) (version 2.19; Stanford University Labs, Stanford, CA, USA).⁽³⁵⁾ The PAM uses soft thresholding to produce a shrunken centroid, which allows the selection of genes with high predictive potential. This made it possible to derive the simplified junctional signature (SJS) from the CJS, including all investigated mRNA transcripts. The data analysis and the statistical evaluation of tissue samples were performed with the SPSS 15.0 Family Pack (SPSS, Chicago, IL, USA). In the training cohort, all proteins were included in the first analysis testing the complex junctional profile (CJP). The latter score was reached when considering all scores of all proteins, and taking their arithmetic average as a numerical variable. All individual values of the distinct scores of IHC were included in the statistical evaluation. The Mann–Whitney *U*-test was performed for non-parametric statistical analyses. Hierarchical clustering was used to rank the protein expression data according to their contribution to the identification of prognostic groups. Similar to the gene expression signature, this helped to define those proteins (simplified junctional profile [SJP]) that were able to define the prognostic subgroups by themselves. Combining the overlapping members of the gene and protein expression methods resulted in the claudin-4 and e-cadherin score (CURIO), which

was tested to predict survival in the validation cohort. The contribution of expression data to predict relapse-free survival (RFS), distant metastasis-free survival (DMFS), and overall survival (OS) was displayed according to the Kaplan–Meier method, and statistically supported with log–rank test. For the multivariate analysis, the Cox regression method was applied. *P*-values of <0.05 were considered to be statistically significant.

Results

Claudin and E-cadherin mRNA expression in the public dataset-based training set. First, a CJS was used, including the average expression of the following genes: *CDH-1*, *CLDN-1*, *-3*–*11*, and *-14*–*18* (Fig. 1a). The predictive value of the CJS was significant in all the prognostic estimate aspects (*P*/RFS/ = 2.4E-07, *P*/DMFS/ = 0.0064, and *P*/OS/ = 0.00041).

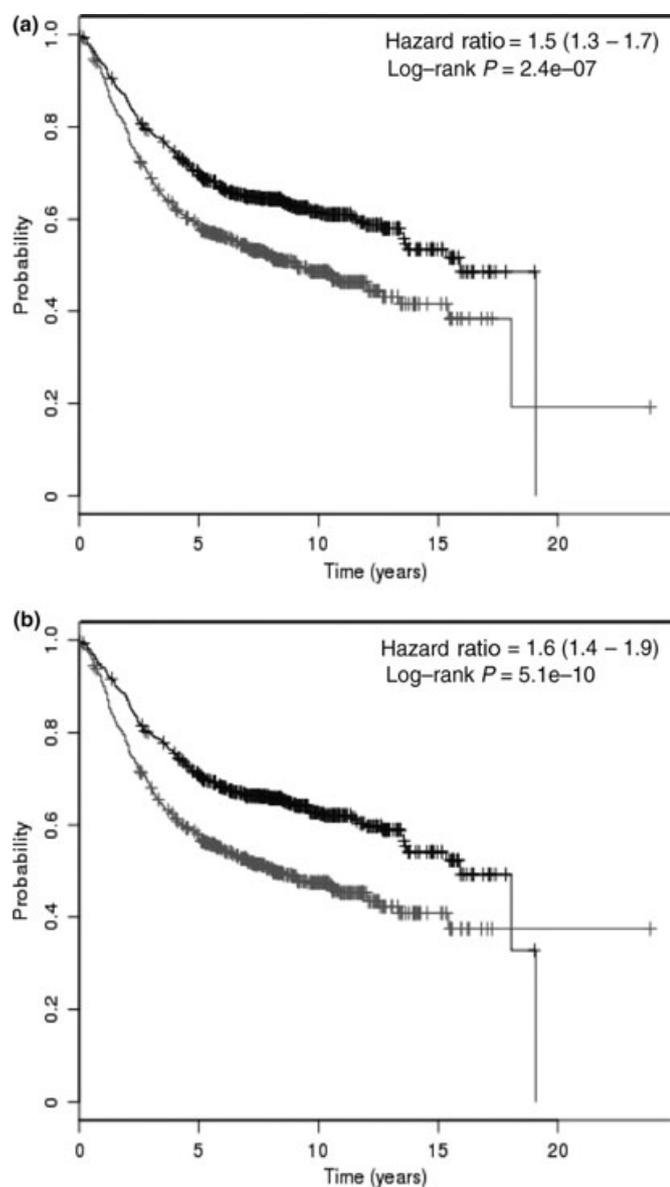


Fig. 1. (a) Kaplan–Meier curve showing the distinguished groups according to expression of the complex junctional signature in the datasets. (b) Curve showing the distinguished groups according to the expression of the simplified junctional signature in the datasets. (—) Gene_expression = 0, (—) gene_expression = 1.

To further refine our analysis, the top genes were ranked based on their centroid plots (displaying the contribution of genes to the definition of prognostic subgroups in order of their strength), resulting in a more powerful predictive capacity for outcome. Based on the average expression of *CDH-1*, *CLDN-3*, *-4*, and *-7*, this SJS has performed as follows (*P*/RFS/ = 5.1E-10, *P*/DMFS/ = 0.00041, and *P*/OS/ = 0.00018). The elevated expression (median <) of mRNA resulted in poor outcomes, as compared to the lower expression (< median) of this signature (Fig. 1b). Of note, these genes have the best estimated quality of the probe set (average expression >500 MAS-5-normalized value), as compared to other CLDN genes.

The database rendered feasible to test the SJS signature in the ER-positive and ER-negative patient cohorts separately. The SJS signature was predictive for DMFS in the ER-positive group (*P* = 0.043), especially in the ER-positive, lymph node (LN)-negative subgroup (*P* = 0.010). When considering ER-negative cancers, the SJS performed even better; it was able to predict RFS and DMFS in the ER-negative group (*P*/RFS/ = 0.0037 and *P*/DMFS/ = 0.0052), and even in the ER-negative, LN-negative subgroup (*P*/RFS/ = 0.0087; *P*/DMFS/ = 0.013). The sample number was too low for meaningful analysis in the ER-negative, LN-positive group (Fig. S3).

Expression of CLDN proteins in breast cancer intrinsic subtypes in our tissue-based training set. The expression of E-cadherin and the CLDN-1–5 and -7 proteins was examined in breast carcinomas, according to previously-defined subtypes. The expression of CLDN-1 was lowest in the luminal B subtype, and CLDN-4 was less expressed in luminal A cancers. E-cadherin showed the highest expression among HER-2+ tumors (Fig. 2). There was no single marker distinguishing TNBC from other subgroups (Fig. 3).

Claudin proteins distinguish prognostic groups in the training set of breast cancers based on IHC. In line with bioinformatics, we investigated the expression of E-cadherin and the CLDN-1–5 and -7 proteins in our breast carcinoma cases to test their relevance as prognostic factors. All scores of the evaluated proteins were included in the index signature (CJP), reflecting the average of all individual expression values. Groups were created at the median level of the combined scores (*P* = 0.006; Fig. 4a).

In the next step, the CJP was investigated for its main drivers. The proteins were ranked according to their contribution to the

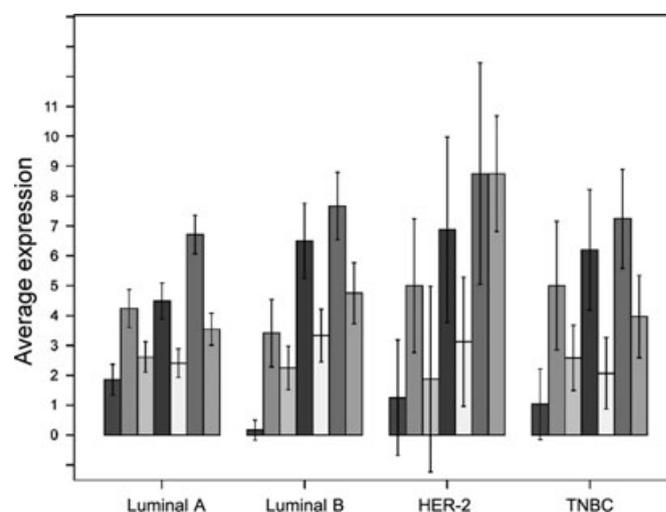


Fig. 2. Expression of claudin-1–5, -7, and E-cadherin in subtypes of breast cancer, and expression of claudins in intrinsic breast cancer subtypes luminal-1. HER-2, human epidermal growth factor receptor-2; TNBC, triple-negative breast cancer. (■) Claudin-1, (▣) claudin-2, (▤) claudin-3, (▥) claudin-4, (▦) claudin-5, (▧) claudin-7, (▨) E-cadherin.

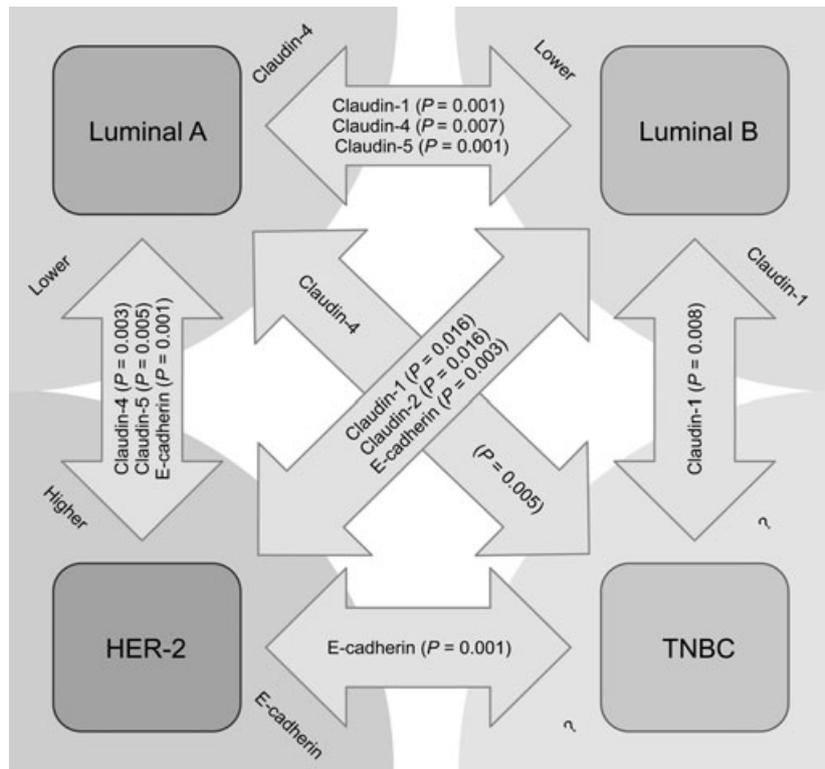


Fig. 3. Expression of claudins in intrinsic breast cancer subtypes Luminal A and B. Significance levels of comparison based on the Mann–Whitney *U*-test of the expressed claudins between the breast cancer subtypes. HER-2, human epidermal growth factor receptor-2; TNBC, triple-negative breast cancer.

CJP with hierarchical clustering (Fig. S4). The analysis revealed that the CLDN-2, -4, and E-cadherin protein expressions averaged were able to distinguish between poor versus good prognostic groups with similar confidence as the CJP, resulting in an SJP ($P = 0.007$). All components were able to distinguish prognostic subgroups by themselves (Fig. S5), but none performed as good as the SJP (Fig. 4b).

Identification and validation of CURIO based on correlation to survival in an independent cohort. We were able to select the SJS *in silico* based on the combined mRNA expression of *CDH-1*, *CLDN-3*, -4, and -7 for a robust prediction of outcome. This overlaps with the training cohort-defined protein expression-based SJP consisting of CLDN-2, -4, and E-cadherin. Thus, we aimed to validate the score-designated CURIO in an independent cohort of 387 patients.

Separated at the median, the CURIO was able to show stronger predictive power for RFS (hazard ratio [HR] = 1.51, 95% confidence interval [CI]: 1.04–2.19, $P = 0.029$; Fig. 5) than the expression of CLDN-4 and E-cadherin individually (HR = 1.43, 95% CI: 1.02–2.03, $P = 0.038$, and HR = 1.39, 95% CI: 1.01–1.90, $P = 0.039$, respectively).

Next, the treatment data were correlated to CURIO. None of the chemotherapy or radiotherapy data showed a correlation with CURIO based on the chi-square test (Pearson's χ^2 -test: 0.822, $P = 0.191$; Pearson's χ^2 -test: 5.124, $P = 0.346$, respectively). To support this, the treatment groups underwent further analysis: tumors with no treatment following surgery, either radiotherapy or chemotherapy, or both radiotherapy or chemotherapy following surgical removal of the tumor, were separately tested for impact of the CURIO on prognosis. All the treatment groups showed the expected trend, although they did not turn out to be significant in either comparison (Fig. S6).

Cox multivariate regression analysis was performed, considering the CURIO, grade, vascular invasion, necrosis, lymph node

status, and subtype. In the pretest, the CURIO was correlated with tumor size ($P = 0.040$), histological type ($P = 0.001$), and Nottingham Prognostic Index (NPI) ($P = 0.004$) with χ^2 -test analysis, thus these variables were omitted from the Cox multivariate regression test. The CURIO, vascular invasion, and intrinsic subtype kept their predictive power after this analysis (Table 2).

Performance of CURIO in the distinct intrinsic subtypes of the validation cohort. The CURIO was predictive for prognosis in luminal A breast tumors, showing the expected distribution of high expression, that is, worse prognosis ($P = 0.006$). In luminal B tumors, the trend was opposite: the higher expression value of the CURIO resulted in a better outcome, as compared to the lower expression split at the median again (Fig. 6), but the result was not significant ($P = 0.198$).

In the ER-negative subtypes, the CURIO did not provide any information on the outcome of HER-2-positive tumors ($P = 0.547$), while in TNBC, the same effect was seen as in the majority of cases; the lower CURIO value resulted in better outcome measures ($P = 0.047$).

Discussion

In the present study, we identified a signature (SJS) based on the expression of selected CLDN and E-cadherin in datasets containing mRNA expression data of 1809 breast cancer patients.⁽³³⁾ In a separate cohort of 197 patients using protein expression on TMA, we identified a similar index (SJP) overlapping with SJS.

Regarding the defined signature at the mRNA level, *CLDN-3*, -4, -7, and *E-cadherin* have been identified by others at the same time as the present study was conducted,^(1,4) emphasizing the role of these molecules' expression in the prognosis of breast cancer. One has to note that these genes have the best estimated quality of the probe set, as compared to the CLDN genes, thus the selection might have technical origin.

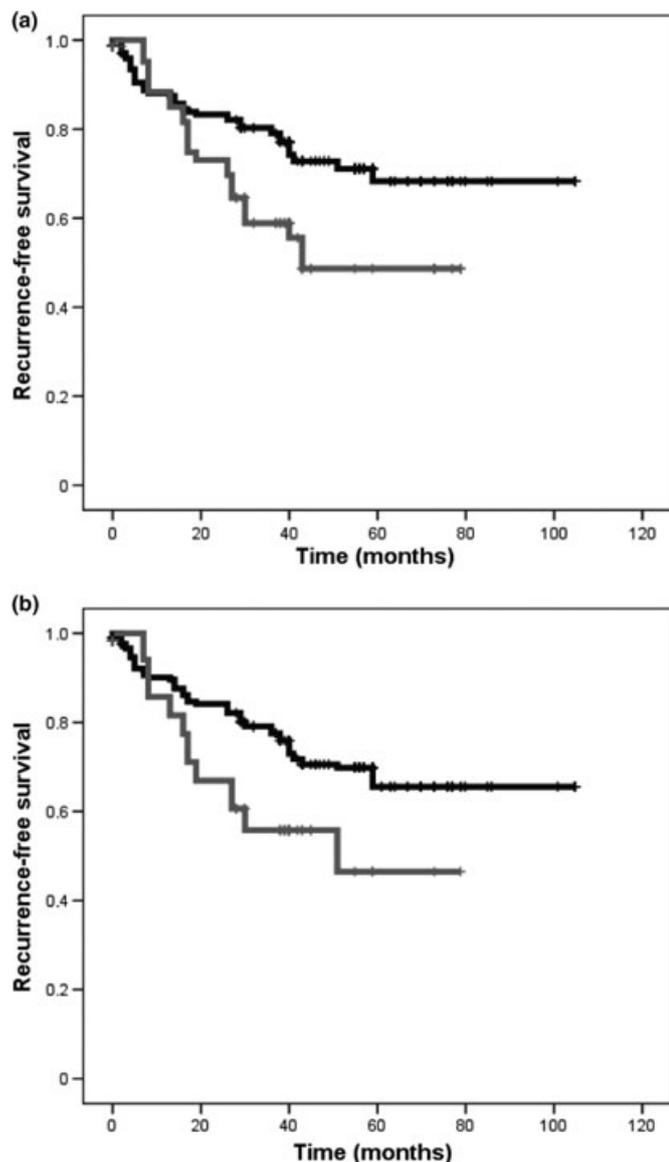


Fig. 4. (a) Kaplan–Meier curve showing the distinguished groups according to expression of the complex junctional profile in the tissue samples. (b) Curve showing the distinguished groups according to expression of the simplified junctional profile in the tissue samples. (—) Low (< median), (---) high (< median).

The SJS was able to predict DMSF and its predictive power, even improved in ER-positive lymph node negative tumors. In the ER-negative group, the signature provided almost the same performance, predicting RFS and showing DMFS tendency. The same was true for the ER-negative, LN-negative cancers, although the lower number of ER-negative tumors did not make a complete analysis feasible. Therefore, analyses in an even larger dataset are needed, because most HER-2-positive and TNBC tumors had high expression of these molecules in this analysis, which in the majority of cases, results in poor prognosis. Also regarding claudin-low tumors, a significantly larger number of patients need to be investigated in depth for CLDN tumor expression. Recent studies also focus on ER-negative carcinomas to define their prognosis and to predict their response to treatment. Human epidermal growth factor receptor-2 amplified breast cancer has become the representative of targeted cancer therapy.⁽³⁶⁾ The results showed that triple-negative carcinomas

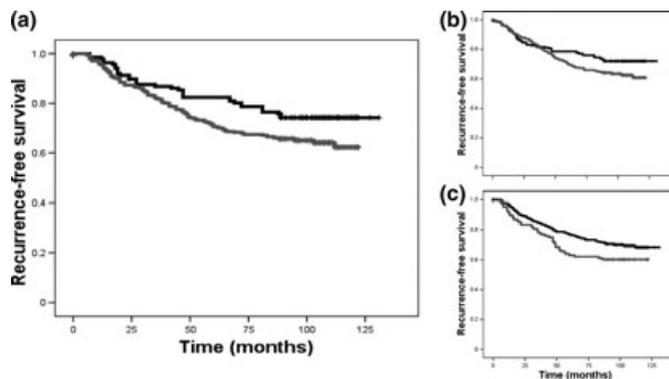


Fig. 5. (a) Kaplan–Meier curve showing the distinguished groups according to expression of the claudin-4 and E-cadherin score in the tissue samples. (b) Kaplan–Meier estimates of E-cadherin on relapse-free survival. (c) Kaplan–Meier graph of claudin-4 expression predictive of relapse-free survival. (—) Low (< median), (---) high (< median).

Table 2. Results of the Cox multivariate analysis with hazard ratios (HR) and 95% confidence intervals (CI)

Parameter	P-value	HR	95% CI	
			Lower	Upper
CURIO	0.040	1.503	1.02	2.216
Subtype	0.001	1.064	0.59	1.918
Vascular invasion	0.011	0.704	0.31	1.808
Lymph node mets	0.091	0.791	0.6	1.038
Grade	0.767	1.037	0.82	1.32
Necrosis	0.232	2.233	0.72	8.435

CURIO, claudin-4 and E-cadherin score.

show the best response to chemotherapeutic agents⁽³⁷⁾ and came into focus in search of tailored therapeutic approaches (platinum agents and poly[ADP-ribose] polymerase [PARP] inhibitors) and diagnostic key markers (e.g. CLDN).^(1,38,39)

In tissue-based investigations, there is a frequent discrepancy between reports regarding CLDN expression.^(15–18,40) In this analysis, we investigated the expression of CLDN and E-cadherin for breast cancer intrinsic subtypes. In 197 cases representing all subtypes reflected by IHC characterization, CLDN-1 was expressed predominantly in luminal A tumors, while CLDN-4 and E-cadherin tended to be expressed in ER-negative (HER-2 and TNBC) tumors at a higher level. The TNBC tumors seem to form a heterogeneous group, according to CLDN expression. In our training cohort, we found that CLDN-2, -4, and E-cadherin expressions were the most powerful profile to predict the time of RFS, which was similar to earlier studies.

The CURIO, the combination of CLDN-4 and E-cadherin, was predictive for prognosis in general, according to high expression, that is, worse prognosis, and lower expression, resulting in a better outcome, especially in luminal A cases. Additionally, TNBC might not only be heterogeneous according to the CLDN expression, but there is a group among the luminal tumors that might show the characteristics of claudin-low tumors. This might shed light on a previously described subgroup of luminal tumors, which did not detach themselves in repeated observations,⁽⁴¹⁾ and shared features with triple-negative and HER-2-amplified breast tumors.⁽⁴²⁾ In HER-2-positive tumors, the CURIO did not provide any information on outcome, while in TNBC, surprisingly, the same effect was seen as in the majority of cases; a lower CURIO resulted in better outcome measures. Thus, we suggest that with the addition of

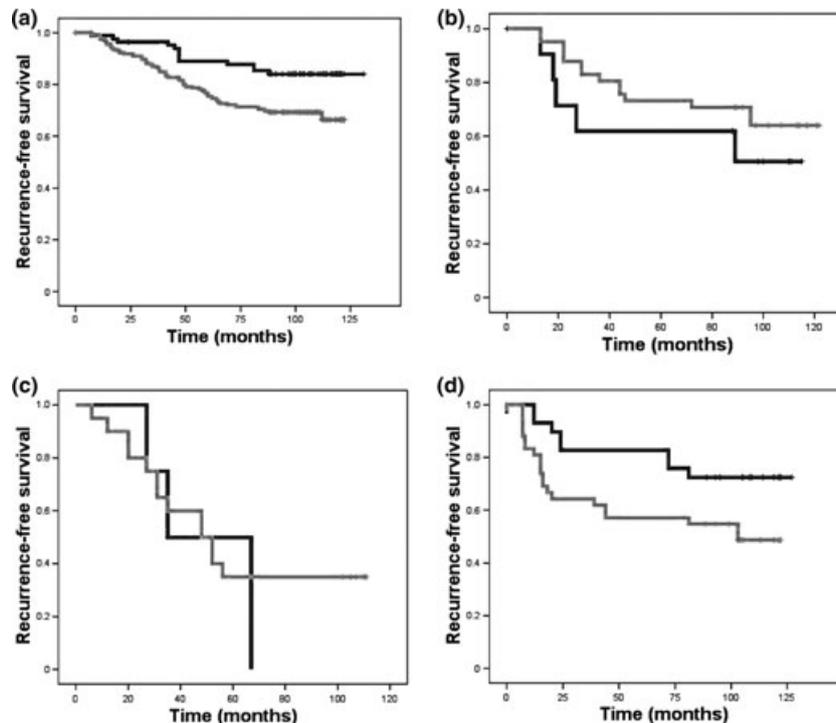


Fig. 6. Kaplan–Meier curve showing the prognostic groups according to the expression of the claudin-4 and E-cadherin score in the luminal A (a), luminal B (b), human epidermal growth factor receptor-2 (HER-2) (c), and triple-negative breast cancer (d) subtypes. (—) Low (< median), (—) high (< median).

CLDN-4 and E-cadherin IHC, the prognosis of breast cancer can be further refined in the routine setting.

There are two major advances of the CURIO over the variables (grade, vascular invasion, necrosis, lymph node status, and subtype). First, these variables depend on the pathological examination of the tissue, second, their examination is less objective than the CURIO.⁽⁴³⁾ Evaluation of IHC is semi-quantitative; therefore, we position the CURIO in between the interobserver variable clinicopathological classifiers and the microarray/PCR-based, more objective tests, especially for those practices with limited resources.

As chemotherapeutic and radiotherapeutic treatment data were available, the CURIO was also tested in treatment groups. Although this comparison could show that the score might be prognostic in all the different treated cohorts, a study with a larger number of patients needs to evaluate this question; this is a limitation of the study.

Numerous parameters were implicated in the prediction of breast cancer prognosis. We slowly start to understand that the picture is extensively complicated: a certain factor and its relation to a biological function and prognosis can only be used under certain circumstances (e.g. different prognostic informa-

tion according to intrinsic subtype of breast cancer). The classification of tumors based on expression signatures and marker profiles can help us to understand the diversity of neoplastic disease and change a paradigm in our concept regarding breast cancer.

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Disclosure Statement

There is no financial or personal interest in relation to the work described.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Fig. S1. Recurrence-free survival curves according to histology, grade, and intrinsic subtype are shown in the training and validation cohort of patient samples.

Fig. S2. Immunostaining for E-cadherin and claudin-4.

Fig. S3. Kaplan–Meier graphs showing the simplified tight junction signature's performance in the prediction of relapse-free, overall, and distant metastasis-free survival.

Fig. S4. Hierarchical clustering showing the contribution of the investigated proteins to the delineation of breast cancer cohorts.

Fig. S5. Kaplan–Meier graphs of the groups defined by the expression (below and above median) of evaluated claudin and E-cadherin proteins, individually.

Fig. S6. Performance of the claudin-4 and E-cadherin score on Kaplan–Meier graphs in the breast cancer groups with different oncological treatment.

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