Increased Expression of Mitotic Checkpoint Genes in Breast Cancer Cells with Chromosomal Instability

Bibo Yuan, Yi Xu, Ju-Hyung Woo, Yunyue Wang, Young Kyung Bae, Dae-Sung Yoon, Robert P. Wersto, Ellen Tully, Kathleen Wilsbach, and Edward Gabrielson

Abstract

Purpose: Most breast cancers have chromosomal instability that seems related to defective mitotic spindle checkpoint controls. Because the molecular basis of this defect is unknown, we evaluated breast cancer cell lines and tissues for possible defects involving the major mitotic checkpoint genes responsible for maintaining chromosomal stability.

Experimental Design: We analyzed sequences and expression levels (RNA and protein) of eight major spindle checkpoint genes (MAD1L1, MAD2L1, MAD2L2, BUB1, BUB1B, BUB3, CDC20, and TTK) in a panel of 12 breast cancer cell lines, most with established genetic instability and defective spindle damage checkpoint response. mRNA levels of these genes were also measured in primary tumor samples, and immunohistochemical staining was used to evaluate BUB1B protein levels in a panel of 270 additional cases of breast cancer.

Results: No functionally significant sequence variations were found for any of the eight genes in the breast cancer cell lines with chromosomal instability. More surprisingly, the mRNA and protein levels for these checkpoint genes are significantly higher in the genetically unstable breast cancer cell lines and in high-grade primary breast cancer tissues than in the stable (and checkpoint proficient) MCF-10A and normal mammary epithelial cells, or in normal breast tissues. In fact, overexpression of the BUB1B protein is a marker that recognizes nearly 80% of breast cancers in paraffin-embedded tissues.

Conclusions: Defective mitotic spindle checkpoints in breast cancer are most likely not caused by low expression or mutations of these eight checkpoint genes. High levels of these particular transcripts could represent a cellular compensation for defects in other molecular components of the mitotic spindle damage checkpoint, and increased expression of these genes might be markers of breast cancers with chromosomal instability.

Most breast cancers have significantly aberrant genomic structure, including abnormal numbers of chromosomes. We have previously shown that in breast cancer cell lines, chromosome numbers are both variable and unstable (1), a phenomenon that seems related to defective mitotic spindle checkpoint controls. This chromosomal instability in breast cancer is similar to what has been observed in other cancers, where defective mitotic spindle checkpoint genes have been implicated as a basis of chromosomal instability. For example, mutations in the BUB1 mitotic checkpoint gene were initially reported in a small number of colorectal cancers with chromosomal instability (2, 3). Subsequently, mutations of BUB1 were reported in colon and pancreatic cancers (3, 4), and a truncating mutation of the MAD2L1 gene was reported for a single breast cancer cell line (4).

Further analyses of the BUB1, BUB1B, and MAD2L1 checkpoint genes, however, have revealed that these mutations are relatively uncommon in cancer. Supporting a possible alternative mechanism for reducing the activity of checkpoint proteins, several studies have provided evidence that low expression levels of key mitotic spindle checkpoint genes could contribute to defective spindle checkpoint controls in cancer. For example, expression of BUB1 is decreased in many colorectal cancers without mutations (3), and MAD2L1 is reportedly underexpressed in some breast and ovarian cancers (5). Such reduced expression apparently has functional significance, because deletion of one MAD2L2 allele results in a defective mitotic checkpoint in both human cancer cells and murine primary embryonic fibroblasts (6) and haploinsufficiency of BUB1B in mice results in defective mitotic arrest as well as tumors (7).

Based on such functional studies, mutations or underexpression of mitotic spindle checkpoint genes could still logically be predicted to play a role in causing genomic instability in breast cancer, and the limited analysis of these genes to date certainly does remove these genes from suspicion.

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Table 1. Primers for real-time PCR

<table>
<thead>
<tr>
<th>Gene</th>
<th>Reference sequence</th>
<th>Forward primer</th>
<th>Reverse primer</th>
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<tbody>
<tr>
<td>BUB1</td>
<td>NM_004336</td>
<td>GAGTGTACATCTTTACGTTGT (633-653)</td>
<td>ACAAACCTGCTCAACATCAAC (734-754)</td>
</tr>
<tr>
<td>BUB1B</td>
<td>NM_004725</td>
<td>ACGTTATTTAGAAAGCTGTAAG (432-453)</td>
<td>CATATCAAGGCTGCTATTG (529-548)</td>
</tr>
<tr>
<td>BUB3</td>
<td>NM_002358</td>
<td>GCCGCGCTTGTGTGTGT (47-65)</td>
<td>AGTAAAGGTTTTGACAGGATAT (195-206)</td>
</tr>
<tr>
<td>MAD2L1</td>
<td>NM_003550</td>
<td>TACCAAGATGACATCACCA (2091-2110)</td>
<td>TACTCCAGTACGTCATCTTG (1924-2023)</td>
</tr>
<tr>
<td>MAD2L2</td>
<td>NM_006341</td>
<td>TGACATCTCCTCCTGTG (191-210)</td>
<td>TCTGCTGATAACTGTCATGC (288-308)</td>
</tr>
<tr>
<td>CDC20</td>
<td>NM_001255</td>
<td>GCTGCTGTCCTCCTGCATTAC (1253-1343)</td>
<td>ATGGTGACCTTATGTTGCAG (1420-1440)</td>
</tr>
<tr>
<td>TTK</td>
<td>NM_003318</td>
<td>AATGCTGGAAATGCGCTG (608-627)</td>
<td>GAAACGGAAGATGCTTTCG (707-727)</td>
</tr>
<tr>
<td>ACTB</td>
<td>NM_001101</td>
<td>AATCTGGACACACACCTTCTA (325-345)</td>
<td>ATAGCACAGGTCGCTGATAA (474-494)</td>
</tr>
</tbody>
</table>

In this study, we comprehensively evaluated eight major mitotic spindle checkpoint genes in 12 breast cancer cell lines that have been previously characterized for chromosomal instability and mitotic spindle defects and in primary tumor samples of high-grade breast cancers. Specifically, we sequenced transcripts of the MAD1L1, MAD2L2, MAD2L2, BUB1, BUB1B, BUB3, CDC20, and TTK genes and measured mRNA levels by real-time PCR and protein levels by immunoblot. Notably, the MAD1L1, MAD2L2, BUB3, TTK, and CDC20 checkpoint genes have not, to our knowledge, been previously evaluated in breast cancer (other than measurements of transcripts of these genes in microarray analyses). We found no sequence variations of any of these genes that would be suggestive of a functionally significant somatic mutation. Surprisingly, we found increased rather than decreased levels of checkpoint gene transcripts in the breast cancer samples compared with those in primary breast epithelial cells. Extending these findings, we tested a large series of breast tissues for expression of a checkpoint gene protein as a potential marker for breast cancer.

Materials and Methods

Breast cancer cell lines, culture conditions, and primary breast cancers.
The 12 breast cancer cell lines (MDA-MB-231, HCC1806, T47D, HCC1937, HCC38, MCF7, HCC1143, BT549, SKBR3, BT-20, HS578T, and DU4475) and the nontumorigenic breast cancer epithelial cell line MCF10A were obtained from the American Type Culture Collection (Manassas, VA) and cultured in recommended medium at 37°C (Table 1). Immunoblot analysis of proteins. Cells were harvested and lysed in buffer containing 50 mmol/L Tris-HCl (pH 7.7), 150 mmol/L NaCl, 0.5% NP-40, 1 mmol/L DTT, 10% glycerol, and 0.5 mmol/L protease inhibitor cocktail (Sigma, St. Louis, MO). Samples of the lysates (50 μg) were then separated using SDS-PAGE electrophoresis and transferred to Bio-Rad (Hercules, CA) membranes. Specific antisera used to

(Qiagen, Valencia, CA), according to manufacturer's protocol. DNA synthesis was done using Oligo(dT) 12-18 (Invitrogen, Carlsbad, CA) and Superscript II RNase H reverse transcriptase (Invitrogen), following the manufacturers' recommendations. PCR amplifications were done using Platinum Taq DNA Polymerase (Invitrogen) with the following conditions: 35 cycles at 94°C for 30 seconds, 60°C for 30 seconds, and 72°C for 1 minute, with a final extension step of 72°C for 5 minutes. Reverse transcription-PCR products were purified using a QIAquick PCR purification kit (Qiagen), and automated fluorescent sequencing was done using appropriate primers (sequences available upon request) on ABI Prism model 3700 automated sequencer (Applied Biosystems, Foster City, CA). Sequences were analyzed using National Center for Biotechnology Information Blast databases and softwar. Each sequence was verified twice, using primers in both the forward and reverse directions. Heterozygous as well as homozygous sequence variants were detected by this method.

Real-time quantitative PCR measure expression level of mitotic checkpoint genes. Total RNA was extracted as above. The primers for SYBR Green real-time quantitative PCR were designed specific for each checkpoint gene and for ACTB (β-actin) as an endogenous control (Table 1). Quantification was based on standard curves constructed by serial dilutions of RNA. The assays were repeated in their entirety for each measurement.

Multiplex RCR was done in 96-well plates using 50 ng RNA per assay and Taqman reverse transcription reagents and SYBR Green PCR master mix (Applied Biosystems). PCR conditions were 30 minutes at 48°C and 10 minutes at 95°C followed by 40 cycles at 95°C for 30 seconds and 60°C for 1 minute. Data were collected using the ABI PRISM 7900HT SDS analytic thermal cycler (Applied Biosystems). Each sample was tested in triplicate, and dissociation curves of each sample were used to check the specificity of amplification. For verification of dissociation curve results, PCR reactions were examined by 2% agarose gel electrophoresis. All experiments with intra-assay or inter-assay coefficient of variation of >10% were repeated. The relative expression level of each gene was normalized to the level present in MCF10A cells, using the level of ACTB as a reference standard.

Cell sorting. To isolate G0-G1 and G2-M populations of cells, cultures were harvested at about 80% confluency and resuspended in prewarmed RPMI 1640 containing 2% fetal bovine calf serum, at a density of 10^6/mL. Hoechst 33342 (Sigma, Milwaukee, WI) was then added at a concentration of 5 μg/mL, and the suspension was incubated at 37°C for 90 minutes in a shaker bath. Cells were pelleted, resuspended in fresh cold medium, and sorted using FACStar Plus (Becton Dickinson, Mountain View, CA).

Immuno blot analysis of proteins. Cells were harvested and lysed in buffer containing 50 mmol/L Tris-HCl (pH 7.7), 150 mmol/L NaCl, 0.5% NP-40, 1 mmol/L DTT, 10% glycerol, and 0.5 mmol/L protease inhibitor cocktail (Sigma, St. Louis, MO). Samples of the lysates (50 μg) were then separated using SDS-PAGE electrophoresis and transferred to Bio-Rad (Hercules, CA) membranes. Specific antisera used to
probe the membranes included goat polyclonal anti-MAD2L2, rabbit polyclonal anti-CDC20 (Santa Cruz Biotechnology, Santa Cruz, CA), monoclonal anti-BUB1B, monoclonal anti-BUB3 (BD Biosciences, San Diego, CA), and rabbit polyclonal anti-β-actin (Santa Cruz Biotechnology) and visualized with enhanced chemiluminescence (Amersham, Piscataway, NJ).

**Immunohistochemical staining.** Breast cancer tissues from a total of 270 patient samples, represented on tissue microarrays, were analyzed using a 1:100 dilution of the same monoclonal anti-BUB1B antibody described above. Immunohistochemical staining of paraffin-embedded pellets of the cell lines corresponded to the expression seen on immunoblots (data not shown), confirming specificity of the antibody for tissue analysis. Slides were pretreated with steam vapors of Target Retrieval solution (DakoCytomation, Carpinteria, CA) according to manufacturer’s instructions, and immunohistochemistry was developed using the conventional streptavidin-avidin-biotin complex kit from DakoCytomation. Staining was scored on the following scale: 0, no staining; 1+, minimal staining; 2+, moderate to strong staining in at least 20% of cells; 3+, strong staining in at least 50% of cells.

**Results**

**Transcripts of mitotic spindle checkpoint genes lack mutations.** To begin our analysis, we sequenced transcripts of the eight major checkpoint genes in the 12 breast cancer cell lines. A total of nine sequence variations, all previously reported as polymorphisms, were found in the transcripts from the cell lines (Table 2). No sequence variation that would likely result in a functional change in the protein (e.g., change of amino acid charge) was found. Because these breast cancer cell lines with defective mitotic spindle checkpoints do not have mutations of these common checkpoint genes, we conclude that such mutations are not a prevalent cause of chromosomal instability in breast cancer.

**Increased mRNA and protein levels of mitotic spindle checkpoint genes in breast cancer.** Previous studies have implicated decreased expression rather than mutations of checkpoint genes as a cause of defective mitotic spindle damage checkpoints in breast cancer. To determine whether decreased expression of checkpoint genes could be responsible for defective checkpoints seen in most of these cell lines, we quantitatively measured transcripts of the eight major mitotic checkpoint genes in the 12 breast cancer cell lines, in “control” breast tissue, and expression was then compared with levels in MCF10A cells. Scale for relative expression is shown in bar below. NA, not amplified in given sample.

**Table 2. Sequence variations in checkpoint gene transcripts from breast cancer cell lines**

<table>
<thead>
<tr>
<th>Genes</th>
<th>Accession no.</th>
<th>Nucleotide position</th>
<th>Sequence variants</th>
<th>SNP cluster ID</th>
<th>Frequencies of sequence variants</th>
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<tbody>
<tr>
<td>BUB1</td>
<td>AF046078</td>
<td>324</td>
<td>No variants noted</td>
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<tr>
<td>BUB1B</td>
<td>AF046079</td>
<td>1088</td>
<td>AAA (Lys) - AAG (Lys)</td>
<td>rs1801389</td>
<td>2/12-11/12</td>
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<tr>
<td></td>
<td></td>
<td>1206</td>
<td>GCA (Ala) - GGC (Ala)</td>
<td>rs1047130</td>
<td>3/12-10/12</td>
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<tr>
<td>BUB3</td>
<td>AF053304</td>
<td>663</td>
<td>No variants noted</td>
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<td></td>
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<tr>
<td>MAD1L1</td>
<td>AF083811</td>
<td>1673</td>
<td>CGC (Arg) - CAC (His)</td>
<td>rs11557345</td>
<td>11/2-2/12</td>
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<tr>
<td></td>
<td></td>
<td>1698</td>
<td>GCC (Ala) - GCA (Ala)</td>
<td>reported</td>
<td>11/2-2/12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1833</td>
<td>GCC (Ala) - GCT (Ala)</td>
<td>reported</td>
<td>12/12-1/12</td>
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<td>MAD2L1</td>
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<td>No variants noted</td>
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<td>MAD2L2</td>
<td>NM_006341</td>
<td>542</td>
<td>TAT (Tyr) - TAC (Tyr)</td>
<td>rs1801338</td>
<td>11/2-2/12</td>
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</table>

**Fig. 1.** Relative expression levels of checkpoint genes in nonmalignant breast cells (top), breast cancer cell lines (middle), and primary tumor samples (bottom). Expression for each gene was normalized to level of β-actin in each cell line, and expression was then compared with levels in MCF10A cells. Scale for relative expression is shown in bar below. NA, not amplified in given sample.
epithelial cell lines (MCF10A and primary mammary epithelial cells) with intact mitotic spindle damage response, and in tissue samples from high-grade breast cancers.

Unexpectedly, we found almost uniformly increased mRNA transcript levels of these checkpoint genes (MAD1L1, MAD2L1, MAD2L2, BUB1, BUB1B, BUB3, CDC20, and TTK) in the breast cancer cell lines relative to levels in MCF10A and primary mammary cells. The results are summarized in Fig. 1, where relative expression levels for all samples are normalized to those measured in the MCF10A cell line. The relative increases in expression range from up to 11-fold for the MAD2L2 gene and up to 520-fold for the TTK gene. Notably, the levels of the checkpoint genes in the breast cancer cell lines were never found to be below the range of expression measured in the normal breast epithelial cells.

We also measure transcript levels of the eight checkpoint genes in nine different tissue samples of poorly differentiated (Nottingham grade 3) invasive breast cancers. As shown in Fig. 1 (bottom), the levels of these transcripts in the cancer tissues mirrored our findings in the breast cancer cell lines, with almost uniformly increased expression of checkpoint genes in cancer compared with normal breast.

To confirm overexpression of these genes at the protein level, protein levels of four genes (BUB1B, MAD2L1, BUB3, and CDC20) were measured semiquantitatively by immunoblot using commercially available antisera. For these experiments, protein levels in the cancer cells were compared with those in MCF-10A and immortalized, nontumorigenic mammary epithelial cells (ME16C). As shown in Fig. 2, these four checkpoint proteins are generally present in significantly higher levels in the cancer cell lines than in MCF10A or ME16C cells. Although BUB1B protein levels are somewhat lower in several of the cancer cell lines than in the MCF10A cells, all breast cancer cell lines have significantly higher levels of BUB1B than the ME16C cells (Fig. 2) and cultured primary mammary epithelial cells (data not shown). Thus, checkpoint genes seem to be generally expressed at high levels in breast cancer at both the transcriptional and translational level.

Cell cycle variation does not explain high levels of checkpoint gene expression in breast cancer cells. Because previous investigations found checkpoint genes (e.g., CDC20, and mouse BUB1B) to be expressed in a cell cycle-dependent manner (10, 11), we considered the possibility that high levels of checkpoint gene expression in cancer cells simply reflect a high rate of proliferation. Although the rate of proliferation of the cancer cells does not differ significantly from that of MCF-10A cells or early-passage primary mammary cells, we compared expression levels for G0-G1 and G2-M fractions of flow cytometry sorted MCF-7, MDA-231, and primary mammary cells (Fig. 3). As shown in Fig. 3, the difference in expression between G2-M cells and G0-G1 cells is less than the difference in gene expression across unsorted (and unsynchronized) cells. Thus, cell cycle–dependent variation in expression is insufficient to completely explain the high levels of checkpoint gene transcripts observed in breast cancer cells compared with nonmalignant breast cells.

Increased expression of BUB1B characterizes high-grade breast cancer. We tested the commercially available antisera to checkpoint proteins and found that antiserum to the BUB1B protein (but not other antiseria) stains formalin-fixed, paraffin-embedded tissues in a manner consistent with immunoblot results (data not shown). Therefore, we used this antiserum to evaluate expression of BUB1B in a panel of 270 primary breast cancer samples represented on tissue microarrays. Most (77%) of the breast cancers in this set of tumors stained positive (2+ to 3+) for BUB1B, whereas none of the 18 normal breast ductal tissues showed significant staining for this antigen. Representative staining is shown in Fig. 4. The staining in breast cancer for BUB1B is cytoplasmic, similar to the pattern reported for colorectal cancer cells (12). By contrast, for normal colonic epithelium, BUB1B staining is seen with the expected nuclear localization (12), whereas no staining was seen in normal breast epithelium with the conditions used in this study. Some breast cancers show heterogeneous staining for BUB1B (e.g., Fig. 4B).

Remarkably, staining for BUB1B is particularly prevalent in grade 2 (86%) and grade 3 (94%) ductal breast cancers, with many fewer cases of grade 1 ductal cancer (18%) and no cases of mucinous breast cancer staining above background for this antigen (Table 3). Not unexpectedly (because of the high prevalence of BUB1B staining), expression was not found to be
Fig. 4. Immunohistochemical staining for BUB1B in breast cancer tissues. A–C from grade 3 ductal cancers; D, from a grade 1 ductal cancer. A and B, arrows designate nonmalignant breast ducts that do not stain significantly for BUB1B. C, arrow designates area of tumor with minimal staining (heterogeneous expression). A–C, expression was interpreted as 3+; D, expression was interpreted as 0. Photographs were taken at 400× magnification.

a significant independent variable predictive of survival among the patients with cancers represented on the arrays (data not shown).

Discussion

Checkpoint genes, which delay mitosis when chromosomes are imperfectly aligned, have drawn considerable attention for their possible role in the phenomenon of genomic instability in neoplasia. This attention was fueled by early reports showing mutations in the BUB1 gene in some cases of colorectal cancer and low expression of the MAD2L1 gene in one breast cancer cell line. Interestingly, even a hemizygous mutation of BUB1 seems to be functionally significant, and haploinsufficiency of checkpoint genes, such as BUB1B, in genetically engineered mice was sufficient to result in slippage of cells from mitotic arrest and enhancement of tumor development. Thus, whereas checkpoint genes do not have characteristics of classic tumor suppressor genes, it would seem that even partial reduction of function for one of these genes could have profound effects on mitotic stability and maintenance of genomic integrity.

Based on such observations, the role of mitotic spindle damage checkpoint genes in the development of chromosomal instability, mutations, or decreased expression of these checkpoint genes in breast cancer might be expected. However, with one exception (5), previous studies on the checkpoint genes in breast cancer failed to find possible mutations or loss of gene expression for the checkpoint genes examined (4, 13–17). Nevertheless, the fragmented nature of these previous studies, which did not include any analysis of MAD1L1, MAD2L2, BUB3, TTK, or CDC20 genes, does not by any means exclude this class of genes from being involved in the pathogenesis of genomic instability in breast cancer. By conducting a more comprehensive evaluation, we can now be more confident in concluding that neither mutations nor underexpression of these checkpoint genes are responsible for the defective checkpo ints that are so prevalent in this type of cancer.

Although previous studies that have focused specifically on mitotic checkpoint genes in breast cancer have not found increased expression of these genes, it is notable that some microarray-based gene expression profile studies of breast cancer have found elevated levels of selected genes in subsets of breast cancer. For example, levels of BUB1 mRNA were reported to be high in breast cancers with extremely poor outcome (18), and MAD2L1 levels were reportedly elevated in basal-like breast cancers that respond to chemotherapy (19). Although the transcript levels of many checkpoint genes are below the level required for effective measurement by microarray analysis, these results complement our findings in suggesting that elevated transcript levels of checkpoint genes are common in breast cancers, including subtypes of breast cancer with aggressive clinical biology.

When evaluating this gene expression data of cell culture and tissue samples, it is important to recognize that mitotic checkpoint genes are normally expressed in a cell cycle–dependent manner (10, 11). To verify that breast cancer cells are not deficient in checkpoint proteins at the time they are likely needed most, we measured transcripts in G2-M cells isolated by flow cytometry. These measurements confirmed that the high expression of checkpoint genes in cancer cells persists through mitosis. Furthermore, our immunohistochemical staining for BUB1B protein showed expression in mitotic cells as well as nondividing cells. Thus, it seems unlikely that cell cycle–specific deficiencies in checkpoint protein levels are responsible for loss of the checkpoint controls in breast cancer.

What, then, is the significance of overexpression of checkpoint genes in breast cancer? One possible explanation of this observation would be that high expression of these proteins represents a partial compensation for other defects in the mitotic spindle checkpoint. Indeed, total loss of checkpoint gene function actually seems catastrophic, even for cancer cells (20); thus, it would seem reasonable that cells would have such compensatory mechanisms to prevent total chaos at mitosis. Alternatively, it could be speculated that overexpression of checkpoint genes actually contributes to defective checkpoints and genomic instability. The possibility of this apparent paradox is supported by observations that overexpression of wild-type BUB1 or MAD3 gene leads to chromosome instability in yeast (21).

### Table 3. Expression of BUB1B by immunohistochemistry in breast cancer tissues

<table>
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<tr>
<th>Histologic type</th>
<th>No. tested</th>
<th>No. (%) positive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grade 1 ductal</td>
<td>40</td>
<td>7 (18%)</td>
</tr>
<tr>
<td>Grade 2 ductal</td>
<td>76</td>
<td>65 (86%)</td>
</tr>
<tr>
<td>Grade 3 ductal</td>
<td>137</td>
<td>129 (94%)</td>
</tr>
<tr>
<td>Lobular</td>
<td>11</td>
<td>7 (64%)</td>
</tr>
</tbody>
</table>

Note: Cases with 0 or 1+ staining (similar to normal breast tissue) are classified as negative, and cases with 2+ or 3+ staining are classified as positive. The percentages of positive cases for grade 1 ductal and mucinous breast cancers are significantly less (P << 0.001 by χ² statistic) than for grade 2 and 3 ductal breast cancers. Overall, 77% of tumors stained positive for BUB1B.
If overexpression of checkpoint genes contributes to cancer cell survival, or if this overexpression contributes to the malignant phenotype, it is possible that the related pathways could represent potential targets for cancer therapy. A more tangible implication of this overexpression is that increased expression of these genes could be markers of genetic instability in breast cancer. In fact, a single antibody, specific for BUB1B, selectively stained >90% of grade 2 and 3 ductal breast cancers without reacting significantly to normal breast ductal structures. Remarkably, positive staining was seen in relatively few cases of grade 1 ductal breast cancer (18%) and no cases of mucinous breast cancer, which have many fewer genomic alterations than ductal cancers have and thus probably do not have a comparable level of genomic instability (22). Although the sensitivity of this one antibody alone may not be sufficient for application as a diagnostic marker for breast cancer, there is certainly an implication that it could be a part of a panel of markers used to differentiate benign breast cells from malignant cells in some diagnostic situations. Moreover, because the high expression of this protein seems to be relatively selective for high-grade cancers, the potential of this marker for classification of breast cancer should be explored.

Acknowledgments

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References

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