INTRODUCTION

Breast cancer (BC), a worldwide health problem, is the most common malignancy and the leading cause of death in women worldwide. Only 5%-10% of mutations in BRCA genes are associated with familial breast tumours in Eastern countries, suggesting the contribution of other genes. Using a microarray gene expression profiling study of BC, we have recently identified BRIP1 (fivefold up-regulation) as a potential gene associated with BC progression in the Omani population. Although BRIP1 regulates DNA repair and cell proliferation, the precise role of BRIP1 in BC cell invasion/metastasis has not been explored yet; this prompted us to test the hypothesis that BRIP1 promotes BC cell proliferation and invasion. Using a combination of cellular and molecular approaches, our results revealed differential overexpression of BRIP1 in different BC cell lines. Functional assays validated further the physiological relevance of BRIP1 in tumour malignancy, and siRNA-mediated BRIP1 knockdown significantly reduced BC cell motility by targeting key motility-associated genes. Moreover, down-regulation of BRIP1 expression significantly attenuated cell proliferation via cell cycle arrest. Our study is the first to show the novel function of BRIP1 in promoting BC cell invasion by regulating expression of various downstream target genes. Furthermore, these findings provide us with a unique opportunity to identify BRIP1-induced pro-invasive genes that could serve as biomarkers and/or targets to guide the design of appropriate BC targeted therapies.

KEYWORDS
breast cancer, BRIP1, invasion, metastasis, proliferation, targeted therapy
Qatar encompasses numerous risk factors such as late menopause, prolonged hormone replacement therapy, older age at first live childbirth, family history of BC at a young age and the mutations of the breast cancer associated gene 1 and 2 (BRCA1/2) genes. New prognostic biomarkers need to be developed better-targeted therapies against invasive stages of BC to enhance the chance for long-term survival and patient’s quality of life. To achieve this goal, it is imperative to understand the exact signalling pathways associated with the multistage process of metastasis. Invasion, the hallmark of malignancy, is the recurring and defining event in the metastatic process, and elucidation of its mechanisms is critical for developing effective anti-metastatic therapies.

In GCC countries, where the rate of consanguinity is quite high (~50%), a significant number of BC patients are younger and show advanced tumours. In addition, a previous study conducted among Omani females with BC, showed no significant pathogenic BRCA1 gene missense mutations, suggesting the involvement of other genes in BC development. Based on the observations described above, we have previously used microarray analysis to compare RNA samples isolated from 40 malignant breast tumour tissues and 40 normal/benign breast tissues, and identified BRCA1-interacting C-terminal helicase 1 (BRIP1), showing fivefold induction, as a potential gene that might promote BC progression. BRIP1, also known as Fanconi Anaemia Group J Protein (FANCJ) or BRCA1-associated C-terminal helicase (BACH1), was first identified using tandem mass spectrometry by its physical interaction with BRCA1 and also belongs to the Fanconi anemia (FA) genes family. BRIP1 is located on chromosome 17q22, spanning a region greater than 180 kb, starting from 61 679 185 to 61 863 558 base pair with 20 exons and 19 introns. Interestingly, BRCA1 is also located on chromosome 17q21 region, hence in close proximity with BRIP1.

BRIP1 plays major role in DNA repair, type J Fanconi anemia, development of various cancers, including BC. BRIP1, a DNA-dependent ATPase and a 5′-3′ helicase that belongs to the DNA-dependent RecQ DEAH helicase family, interacts with BRCA1 and is involved in double-stranded DNA breaks (DSB) repair during the G2-M phase of the cell cycle as well as in tumour suppression. DNA damage responses and checkpoints, which are crucial for genomic stability. While BRCA1 and BRIP1 work as tumour suppressor genes, when BRIP1 fails to bind BRCA1 in certain conditions, cells become sensitive to different genotoxic stresses with aberrant homologous DNA repair function. Identification of BRIP1 germ line mutations in BC patient with wild-type BRCA1 and BRCA2 suggests a major link between moderate penetrance of BC and BRIP1 mutation.

Based on these observations, we hypothesized that beyond its function as a DNA repair gene, BRIP1 plays a novel role in tumour cell invasion/metastasis. In addition, to providing a better understanding of the mechanisms that underpin BRIP1-mediated tumour cell invasion, this study has validated BRIP1 as a target gene that can be used to design efficient therapeutic strategies against BC.

2 | MATERIALS AND METHODS

2.1 | Cell culture

Human BC cell lines HCC-2218, T47D, BT474, MCF-7, CAMA-1 and the immortalized human breast cell line MCF 10A were obtained from the American Type Culture Collection (ATCC). Immortalized HuMEC cells, MDA-MB-231 and MDA-MB-468 were provided by (Qatar University, Qatar), while HCC-1500 cell line was obtained from (Weill Cornell Medical College, Qatar). HCC-2218, T47D, BT474, MCF-7 and CAMA-1 cell lines were grown in DMEM medium (Gibco), while MDA-MB-231, MDA-MB-468 and HCC-1500 cells were cultured in RPMI 1640 medium. Culture media were supplemented with 10% heat-inactivated Foetal Bovine Serum (FBS) (Thermo Scientific™) and 1% of an antibiotic suspension (Penicillin and streptomycin, Gibco). MCF 10A non-pathogenic breast cell line was grown in HuMEC Basal serum-free medium (Gibco, 12753018) supplemented with HuMEC Supplement Kit (Gibco, 12755013), while HuMEC cells were cultured in keratinocyte serum-free medium (SMF) supplemented with bovine pituitary extract (BPE) (Gibco, 17005042). All cells were maintained with an atmosphere of 5% CO₂ in a humidified incubator adjusted to 37°C.

2.2 | Western blotting

RIPA buffer supplemented with protease inhibitors (Pierce) was used to prepare whole cell lysates. Protein quantification was determined using Pierce™ BCA Protein Assay Kit (Thermo Scientific™) according to the manufacturer’s detailed protocol. Approximately 20 μg of each denatured cell lysates was loaded on a 7.5% SDS-PAGE. Electrophoresis was performed at 70V for 30 minutes and increased to 100V for 1-2 hours in 1X running buffer then transferred into nitrocellulose membrane (Invitrogen). Subsequently, the membranes were blocked with 5% non-fat dried milk in TBS/0.1% Tween 20 for 1 hour prior to probing with primary antibodies; Anti-BACH1 rabbit affinity purified antibody (1:2500, B1310, Sigma) or monoclonal anti-β-Actin mouse antibody (1:2500, A2228, Sigma) overnight at 4°C. The membranes were probed with HRP-conjugated anti-rabbit secondary antibody (1:40 000 dilution, Abnova) to detect BRIP1 protein and anti-mouse secondary antibody (1:2500 dilution, PAB0096, Abnova) to detect β-Actin protein. The signal was revealed with SuperSignal™ West Pico PLUS Chemiluminescent Substrate (Thermo Scientific) and was developed using Chemiluminescent GeneGnome (Syngene). Densitometric quantitative analysis was performed using Image software (NIH Image Soft.).

2.3 | Real-time qRT-PCR

According to the manufacturer’s protocol, 1 μg of total RNA (extracted using GeneJET RNA Purification Kit (Thermo Fisher Scientific) was reversed transcribed into cDNA using the High
Capacity cDNA Reverse Transcription Kit (Applied Biosystems) RT-qPCR assay was performed to determine the expression of BRIP1 using TaqMan® Fast Advanced Master Mix (Applied Biosystems). For each reaction, 1 μL of diluted cDNA (1:4) was added to 10 μL of TaqMan Master Mix, 1 μL of BRIP1 Gene Expression TaqMan® Assays FAM-MGB Probe (4351372, Applied Biosystems), and 1 μL of GAPDH Gene Expression TaqMan® Assays VIC-MGB Probe (4448489, Applied Biosystems) as an endogenous control, and 7 μL of nuclease-free water. The reaction was performed using the QuantStudio™ 6 Flex Real-Time PCR System (Applied Biosystems, Inc) as follows: 10 minutes at 95°C (stage 1); 20 seconds at 95°C and 20 seconds at 60°C for 40 cycles (stage 2). The results were analysed using the QuantStudio™ 6 software.

2.4 | siRNA transfection

Breast cancer cells were transfected with smart pool BRIP1 siRNA (50 nmol/L) (M-010587-00-0010, Dharmacon Products) and Non-Targeting siRNA Pool (si-Ctrl) (D-001206-14-05, Dharmacon Products) in Opti-MEM medium (Invitrogen), using RNAi/Max Lipofectamine® (Thermo Fisher Scientific) according to the manufacturer's protocol. Using four siRNA targeting different BRIP1 sequences lowers the likelihood of identifying off- or non-specific targets in subsequent analyses (since the same off-targets are not normally observed with two or more different BRIP1-siRNAs). Cells were incubated for 24, 48 and 72 hours before gene expression analysis. In order to obtain effective gene silencing, the protocol has been standardized after several attempts, and a second transfection performed 24 hours after the first one showed better results. Different siRNA concentrations ranging from 30 to 100 nmol/L were tested, and 50 nmol/L concentration at 72 hours was selected as the optimal concentration showing the highest BRIP1 silencing. Following incubation of the cells with variable siRNA concentrations, the cells were further analysed for gene expression, cell proliferation and cell motility.

2.5 | Functional assays

2.5.1 | Cell proliferation assay

To explore the effect of BRIP1 knockdown on proliferation rate in BC cell lines, Alamar Blue assay was performed according to the manufacturer recommendations (Invitrogen). Briefly, 10,000 cells of BRIP1-siRNA and si-Ctrl-transfected cells were seeded 48 hours after siRNA transfection/100 μL per well in 96-well plates (flat bottom Corning® Costar® cell culture plates). Next day, 10% of Alamar Blue reagent was added to each well after washing the cells twice with PBS, and the cells were incubated at 37°C for 4 hours in a dark chamber. Absorbance was measured at wavelengths 570 and 600 nm using BioTek Epoch2 (Synergy Multi-Mode Reader, Inc). The results are presented as percentage difference in reduction between siRNA-BRIP1 and si-Ctrl-transfected cells.

2.5.2 | In vitro cell invasion and migration assays

Cell migration and invasion assays were performed as we have previously described. Briefly, for migration assay, 3 × 10^5 of MDA-MB-231 or 5 × 10^5 of (MCF-7 and CAMA-1) BRIP1-siRNA and si-Ctrl-transfected cells were added directly to 8 mm PEC Transwell (without matrigel) chambers (Corning) for migration assays. For invasion assay, (matrigel coated) chambers (Corning) were initially incubated at 37°C for 2 hours. After incubation, transfected cells of 1 × 10^5 of MDA-MB-231 or 10 × 10^5 of (MCF-7 and CAMA-1) were added to the upper matrigel coated Transwell chambers. A volume of 650 μL media, containing 10% FBS as a chemoattractant, was added to the lower chamber. Cultures were maintained for 24 hours for MDA-MB-231 and 48 hours for MCF-7 and CAMA-1. For both migration and invasion assays, membranes were washed, fixed in 4% paraformaldehyde for 10 minutes and stained with 5% crystal violet in ethanol. Non-penetrated cells were removed from the upper chambers using cotton swabs, and pictures were taken from five different microscopic fields using Cell Imaging System (Olympus IX73 inverted microscope). Fields were quantified and analysed using ImageJ software (NIH Image Software).

2.5.3 | Wound healing assay

Briefly, MCF-7, CAMA-1 and MDA-MB-231 cells were transfected with BRIP1 siRNA or non-targeted siRNA (si-Ctrl). Then, the cells were counted and seeded in a 24-well plate with serum-free media. A straight scratch was made in each well using a sterile 10 μL white tip. Cells were washed gently with sterile PBS to remove debris and then cultured in their corresponding complete growth media. The plates were then incubated and photographs were taken at 0, 24 and 48 hours, depending on the cell line used in reference to a marker line for accurate imaging. Results were analysed using the ImageJ software (NIH Image Software).

2.5.4 | Cell cycle

Cell cycle analysis was carried out using fluorescence-activated cell sorting (FACS) method. In both siRNA-BRIP1 and si-Ctrl-transfected, cells were trypsinized using TrypLE reagent (Gibco), fixed and incubated overnight at 4°C. Next day, the cells were centrifuged, washed and then incubated with 40 μg/mL propidium iodide (PI) and 100 μg/mL RNase (Sigma) in the dark at room temperature for 30 minutes. Stained cells were then analysed by BD Accuri™ C6 Flow Cytometer (BD Biosciences). Non-stained and PI-stained cells were used as controls. Cell cycle distribution analysis was determined using (FlowJo™ v10.6.1, LLC) software.
2.6 | Metastasis-associated genes profiling

Predesigned tumour Metastasis Fast 96-well plates (4414098, Life Technologies) containing lyophilized TaqMan® Gene Expression assay was used to determine the expression levels of pro-metastatic genes in BRIP1-siRNA transfected cells compared with siCtrl. Briefly, total RNA was converted into cDNA as described above. The metastasis-associated genes profiling reaction was performed using QuantStudio™ 6 Flex Real-Time PCR System (Applied Biosystems, Inc), according to the manufacturer instructions. The results were first normalized to GAPDH and further analysed to obtain the Relative mRNA expression levels, using the formula $2^{- \Delta \Delta Ct}$. All the reactions were carried out in triplicates and repeated twice.

2.7 | Statistical analysis

In proteomics analysis, Student’s two-tailed test was used to assess the statistical significance of the protein quantification. Statistical significance between groups was assessed using ANOVA tests and Student’s t test. For other experiments, a non-parametric Student's t test was applied using Microsoft Excel 2013 and GraphPad Prism 8. Data of three independent experiments were presented as means ± SD unless otherwise indicated in the legends. P values ≤.05 were considered statistically significant.

3 | RESULTS

3.1 | BRIP1 is highly expressed in different breast cancer cell lines

Both BRIP1 protein and mRNA levels were differentially overexpressed in various BC cell lines compared with control HuMEC and MCF 10A cells (Figure 1). At the protein level, Western blotting analysis followed by densitometric quantification showed relative overexpression of BRIP1 compared with control (Figure 1B). Similarly, BRIP1 mRNA levels showed 1.8 to 14-fold increase in the tested BC cell lines compared with normal/control cells (Figure 1C).

![BRIP1 protein and mRNA expression levels in various BC cell lines](image_url)
3.2 | Down-regulation of BRIP1 using siRNA interference in breast cancer cell lines

Four different Dhramacon SMARTpool siRNAs specific to BRIP1 were mixed, providing both specificity and potency advantages in inhibiting BRIP1 expression in BC cells. The siRNA concentration that resulted in the most efficient silencing of BRIP1 with the least cell toxicity was selected for all experiments. Treatment of selected BC cells with increasing concentrations of siRNA mixture ranging from 30 to 100 nmol/L showed the highest decrease in BRIP1 protein levels by approximately 70% with 50 nmol/L at 72 hours in MCF-7 (Figure 2A). The dose of 50 nmol/L was selected for all other three cell types, showing 80% reduction of BRIP1 in CAMA-1 and MDA-MB-231 (Figure 2B-C), respectively, and 70% inhibition in HCC-1500 (Figure 2D). BRIP1 mRNA levels were significantly decreased in all transfected BC cells compared with si-Ctrl-transfected cells (see Figures S1 and S2 in Supplementary Data).

3.3 | BRIP1 facilitates proliferation in breast cancer cell lines

To examine the effect of BRIP1 inhibition on BC cell proliferation, cells were treated with either BRIP1-siRNA or si-Ctrl, and cellular proliferation was assessed at 24, 48, and 72 hours post-treatment using Alamar blue assay. As shown in Figure 3, cellular proliferation was significantly reduced in si-BRIP1 transfected cells compared with si-Ctrl groups in all studied BC cell lines. Despite a slight variation between the different BC cell lines, there was a decrease by 46.5% in MCF-7, 28.6% in CAMA-1, 48.6% in MDA-MB-231
FIGURE 3  Effect of BRIP1 siRNA suppression on cell proliferation in various breast cancer cell lines. (A) Relative cell proliferation rate at 24, 48 and 72 h post-transfection with the pool of BRIP1-specific siRNAs (50 nmol/L) in MCF-7, CAMA-1, MDA-MB-231 and HCC-1500 breast cancer cell lines. (B) All tested si-BRIP1 BC cell lines showed maximal inhibition in proliferation 72 h post-treatment. The data represent analysis of results from replicate experiments using the mean ± SD (n = 3). ***P < .001

FIGURE 4  si-RNA suppression of BRIP1 induced cell cycle arrest in various BC cells. Representative analysis of Cell cycle phases in (A) MCF-7, (B) CAMA-1, (C) MDA-MB-231 and (D) HCC-1500 BC cells treated with BRIP1-siRNA compared with si-Control transfected cells at 72 h using flow cytometry. (E) Representative qualitative analysis of G0/G1, S, and G2/M cell cycle phases of all BRIP1-siRNA transfected BC cell lines compared with si-Ctrl. The quantitation was done by calculating the area under the curve using Flowjo software and is presented as the mean ± SD for three independent experiments. *P < .05
and 33.5% in HCC-1500 72 hours post-treatment (Figure 3B). Fluorescence-activated cell sorting (FACS) analysis revealed that BRIP1 suppression induced G1/S arrest in all the studied si-BRIP1-transfected BC cells (Figure 4). All the data put together indicate that BRIP1 promotes BC cell proliferation.

### 3.4 | BRIP1 promotes migration and invasion ability of breast cancer cell lines

Wound healing assay results revealed that BRIP1 suppression significantly attenuated the ability of cells to close the gap. Compared with control cells, a relative wound closure of 60% in MCF-7 and MDA-MB-231, and 50% in CAMA-1 was observed (Figure 5). Furthermore, in non-coated Transwell assay, compared with the control groups, the migration ability of si-BRIP1-inhibited cells was significantly reduced by 70% in MCF-7 and MDA-MB-231, and 60% in CAMA-1 (Figure 6A). Suppression of BRIP1 showed significant inhibition of invasion by 50% in MCF-7, MDA-MB-231 and CAMA-1 compared with si-Ctrl-transfected cells (Figure 6B). Together, our results indicate that suppression of BRIP1 inhibited both migration and invasion in all tested BC cell lines.

### 3.5 | BRIP1 promotes cell invasion by modulating expression of an array of related genes

In order to identify potential molecular signalling pathway(s) underpinning the novel role of BRIP1 in BC progression, TaqMan RT-qPCR of 92 different metastasis-associated genes was performed to determine differentially expressed genes in BRIP1-suppressed MCF-7 and MDA-MB-231 cells compared with controls. Analysis of our results showed a significant up-regulation/down-regulation of a group of genes known to regulate both cell growth and cell motility. Among several differentially expressed genes, the present study focused on genes associated with extracellular matrix, adhesion molecules, cell proliferation and motility (C-X-C motif chemokine 12 [CXCL12], Retinoblastoma 1 [RB1], Ras Homolog Family Member C [RHOC], H/K Retrovirus-Associated DNA Sequences [H/KRAS], Epithelial cell adhesion molecule [EPCAM], Avian myelocytomatosis viral oncogene homolog [MYC], SMAD family member 4 [SMAD4], Melanoma Cell Adhesion Molecule [MCAM [CD146]], Alpha-1,6-Mannosylglycoprotein 6-Beta-N Acetylgalcosaminyltransferase [MGAT5] and Matrix Metalloproteinases [MMPs]) was determined (Table 1).

### 4 | DISCUSSION

We have previously employed microarray gene expression profiling and compared RNA samples isolated from malignant breast tumour tissues to normal/benign breast tissues. Among a number of differentially expressed genes, BRIP1, showing a fivefold up-regulation, was identified as a potential gene that might underpin breast tumour progression. Although BRIP1 interacts with BRCA1 to regulate cell cycle and DNA repair mechanisms, the role of BRIP1 in mediating tumour growth and progression has not been examined yet. In the present study, we tested the hypothesis that BRIP1 can promote both BC cell growth and metastasis. The results of the present study are summarized as follows: (a) structural validation experiments were consistent with our previous findings, showing fivefold overexpression of BRIP1 in all types of BC tumour samples compared with normal/benign breast tissues; (b) functional validation approaches

![Figure 5](image-url)  
**Figure 5** Wound-healing assay showing the effect of BRIP1 siRNA inhibition on cell migration in selected breast cancer cell lines (A) MCF-7 (B) MDA-MB-231, and (C) CAMA-1. Graphical representation of the relative wound closure following BRIP1-specific siRNA treatment compared with si-Ctrl at 48 h in MCF-7 and CAMA-1, and at 24 h in MDA-MB-231. Data shown are representatives of three independent experiments under the same conditions. The error bars represent the SD. **P < .01, ***P < .001.
revealed a novel role of BRIP1 in promoting breast tumour cell growth and progression. In fact, siRNA down-regulation of BRIP1 attenuated significantly cell proliferation by inducing cell cycle arrest. Moreover, RNAi-inhibition of BRIP1 significantly reduced migration and invasion of BC cell lines; (c) a unique set of differentially expressed BRIP1-target genes associated with both cell cycle and metastasis seem to underpin BRIP1-promoted BC cell proliferation and invasion.

### 4.1 BRIP1 overexpression in breast cancer

The mutational spectrum of BRIP1 was recently investigated in various BC cell lines using the *Estimate algorithm* of genome-wide copy number analysis and hybrid capture sequencing of 1651 genes showed no BRIP1 mutations in our selected model for functional characterization. Up-regulated BRIP1 levels in malignant breast tumours contradict its role as a tumour suppressor. As an example, the tumour protein 53 (TP53) tumour suppressor gene is overexpressed in colorectal cancer, which is not predictive with its mutational status as an early event, suggesting that TP53 has an oncogenic role independent of the tumour suppression activity. This dual behaviour was also reported for other genes, such as Wilms' tumour 1 (WT1); mutated WT1 led to the onset of kidney tumours, and its overexpression was detected in a subset of human cancers.

Although gene amplification plays a major role in tumorigenesis, especially for solid tumours (reviewed in, the molecular mechanisms of how these genes are amplified are not fully understood yet. Plausible mechanisms of gene amplification may include episome excision, re-replication and unequal exchange.

Bioinformatic analysis of approximately 2000 BC patients, revealed that the 17q23 region was associated with the presence of
oncogenes, BC poor prognosis and tumour progression. Gain of function resulting from amplification of this region has been reported in other cancers, including liver, pancreas, bladder, testis, ovary, lung and brain tumours. Interestingly, the 17q23 region is also involved in the development of BRIP1 gene lies, encompasses known oncogenes RPS6KB1, TBX2 and PPM1D. In particular, TCGA showed a 3.2-fold up-regulation of BRIP1 in breast tumours compared with normal breast tissues. Similarly, our microarray data revealed that BRIP1 had an average of fivefold overexpression as compared to normal breast tissue samples.

Consistent with these observations, our results showed clearly that both the protein and mRNA levels of BRIP1 were overexpressed in various BC cell lines compared with control normal/immortalized and normal/control breast cells, suggesting that BRIP1 might act as an oncogenic driver in BC. Interestingly, previous study revealed the presence of BRIP1 germline mutations in BC patients without any BRCA1 mutation, suggesting a link between BRIP1 mutations and BC susceptibility. Collectively, although BRIP1 is considered as a tumour suppressor gene, it is amplified in sporadic cancers, thus supporting our previous and current findings, suggesting that BRIP1 amplification in sporadic cancers could explain the oncogenic role of BRIP1.

### 4.2 | BRIP1 promotes breast cancer cell proliferation

In order to understand the mechanisms that underpin BRIP1-promoted BC cell proliferation, our results revealed that siRNA BRIP1 suppression, arrested cell cycle at the G1/S phase, and down-regulated the expression of an array of related genes.

**TABLE 1** BRIP1 promotes cell growth and metastasis by modulating the expression of an array of related genes

<table>
<thead>
<tr>
<th>Symbol</th>
<th>TaqMan Assay ID</th>
<th>Description/Main function</th>
<th>Fold change in BC cells vs BC cells</th>
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</thead>
<tbody>
<tr>
<td>CXCL12</td>
<td>Hs00171022_m1</td>
<td>C-X-C Motif Chemokine Ligand 12/Tumour growth and metastasis</td>
<td>−5.8</td>
</tr>
<tr>
<td>RB1</td>
<td>Hs00153108_m1</td>
<td>RB Transcriptional Corepressor 1/Cell growth and cell cycle</td>
<td>−4.8</td>
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<tr>
<td>RHOC</td>
<td>Hs00733980_m1</td>
<td>Ras Homolog Family Member C/Tumour cell proliferation and metastasis</td>
<td>−3.9</td>
</tr>
<tr>
<td>HRAS</td>
<td>Hs00610483_m1</td>
<td>HRas Proto-Oncogene, GTPase/Regulation of cell proliferation</td>
<td>−3.8</td>
</tr>
<tr>
<td>MYC</td>
<td>Hs00153408_m1</td>
<td>MYC Proto-Oncogene, BHLH Transcription Factor/cell cycle progression, apoptosis and cellular transformation</td>
<td>−3.7</td>
</tr>
<tr>
<td>SMAD4</td>
<td>Hs00232068_m1</td>
<td>SMAD Family Member 4/Cell proliferation.</td>
<td>−3.5</td>
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<tr>
<td>KRAS</td>
<td>Hs00158980_m1</td>
<td>KRAS Proto-Oncogene, GTPase/Regulation of cell proliferation</td>
<td>−3.0</td>
</tr>
<tr>
<td>EPCAM</td>
<td>Hs00174838_m1</td>
<td>Epithelial Cell Adhesion Molecule/Proliferation, differentiation and migration.</td>
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</tr>
<tr>
<td>MUC5</td>
<td>Hs00159136_m1</td>
<td>Mucin 5A/Mucin-like glycoprotein 5/Cell adhesion</td>
<td>−2.9</td>
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<tr>
<td>MMP-1</td>
<td>Hs00233958_m1</td>
<td>Matrix metalloproteinase 1/Breakdown of extracellular matrix and metastasis</td>
<td>−2.0</td>
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</table>

Note: The list of selected genes analysed using the TaqMan™ Array Human Tumour Metastasis (Applied Biosystems™). Fold change was calculated by comparison of Comparative Ct values for siRNA-BRIP1 transfected cells compared with si-Ctrl cells for three biological replicates. Statistical analysis was performed using Student’s t-test. Genes with fold changes below 2 or above −2 (Cut-off point) and/or when the P-value > 0.05 were not considered in the table.

BRIP1 promotes breast tumour cell invasion

On the other hand, and to our knowledge, no study has linked BRIP1 to cancer metastasis yet. Our siRNA experiments suggest that BRIP1 up-regulation may promote breast tumour metastasis. In fact, previous studies revealed that overexpression of RhoA GTPase was associated with carcinogenesis. In the present study, RNAi-inhibited
BRIP1 down-regulated Ras GTPases significantly by (−3.9) fold and subsequently suppressed tumour cell invasion.

Furthermore, si-BRIP1 has markedly down-regulated MMP-1 (−2.1 fold), a member of endopeptidase zinc-dependent family that cleave the extracellular matrix.\textsuperscript{44} MMP-1 down-regulation significantly attenuated cell proliferation, migration and invasion and reduced the expression of Myc in MCF-7 and MDA-MB-231 cells.\textsuperscript{45} In addition, BRIP1 might contribute to BC bone metastasis by switching the SMAD pathway; (SMAD4 was down-regulated by (−3.5) fold) from the known tumour suppression role to pro-metastatic one.\textsuperscript{46}

MGAT5 gene is another BRIP1-transcriptional target gene that was down-regulated upon siRNA inhibition of BRIP1 (−2.5 fold). In fact, MGAT5 overexpression has been reported in various human cancers, including hepatocarcinoma, colon cancer and BC.\textsuperscript{47-49} MGAT5 is known to promote both cell growth, cell motility,\textsuperscript{50,51} leading to tumour progression. A recent study demonstrated that restoration of MGAT5 expression in MCF-7 and MDA-MB-231 overcame the inhibitory effect of miR-124 on BC cell progression.\textsuperscript{52}

Also, our results showed that BRIP1 down-regulation reduced the expression of CXCL12 significantly (−5.8 fold). Structure-function studies showed that CXCL12 chemokine is the only ligand for CXCR4, and thus activation of CXC4 depends on the CXCL12-induced chemokine.\textsuperscript{53} Attenuation of either one of them, using neutralizing antibodies, reduced angiogenesis and metastasis.\textsuperscript{54}

Finally, genes coding for cell adhesion molecules, known to mediate BC progression, were also identified in our Taq Man experiments, including EPCAM (−2.9 fold change) and MCAM known as CD146 (−3 fold change). While, EPCAM, which is overexpressed in most human carcinomas, abrogates E-cadherin-mediated cell-cell interaction,\textsuperscript{55} MCAM overexpression is associated with increased expression of epithelial-mesenchymal transition (EMT) biomarkers and cell motility.\textsuperscript{56}

In conclusion, BRCAness status and family history support the idea of the association of other moderate/low penetrance genes in the onset of BC, such as BRIP1, which binds to BRCA1 to maintain genome integrity.\textsuperscript{5} The present study revealed a novel role of BRIP1 in promoting BC cell growth and invasion. In addition, a number of BRIP1-transcriptional target genes associated with cell growth and cell invasion were identified. While these findings support our hypothesis that BRIP1 promotes BC progression, ongoing structural and functional validation experiments in our laboratory aim to shed light on the exact mechanisms by which BRIP1-downstream signaling promotes BC cell growth and cell invasion.

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CONFLICT OF INTEREST
The authors declare no conflicts of interest.

AUTHOR CONTRIBUTIONS
Balsam Rizeq: Conceptualization (supporting); Data curation (lead); Formal analysis (supporting); Funding acquisition (supporting); Investigation (supporting); Methodology (lead); Validation (lead); Writing-original draft (lead); Writing-review & editing (supporting).

Saïd Sif: Formal analysis (supporting); Methodology (equal); Supervision (equal); Writing-review & editing (equal).

Gheyath K. Nasrallah: Formal analysis (supporting); Writing-review & editing (supporting).

Allal Ouhtit: Conceptualization (lead); Data curation (equal); Formal analysis (equal); Funding acquisition (supporting); Investigation (lead); Methodology (supporting); Project administration (lead); Supervision (lead); Validation (lead); Writing-original draft (supporting); Writing-review & editing (equal).

DATA AVAILABILITY STATEMENT
All the data needed to evaluate the conclusion section are provided in the paper and/or the Supplementary Materials. Additional data related to this paper could be made available upon request from the corresponding author.

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REFERENCES


SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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