Allele-specific regulation of FGFR2 expression is cell type-dependent and may increase breast cancer risk through a paracrine stimulus involving FGF10

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Abstract

Introduction: SNPs rs2981582 and rs2981578, located in a linkage disequilibrium block (LD block) within intron 2 of the fibroblast growth factor receptor 2 gene (FGFR2), are associated with a mildly increased breast cancer risk. Allele-specific regulation of FGFR2 mRNA expression has been reported previously, but the molecular basis for the association of these variants with breast cancer has remained elusive to date.

Methods: mRNA levels of FGFR2 and three fibroblast growth factor genes (FGFs) were measured in primary fibroblast and epithelial cell cultures from 98 breast cancer patients and correlated to their rs2981578 genotype. The phosphorylation levels of downstream FGFR2 targets, FGF receptor substrate 2α (FRS2α) and extracellular signal-regulated kinases 1 and 2 (ERK1/2), were quantified in skin fibroblasts exposed to FGF2. Immunohistochemical markers for angiogenesis and lymphocytic infiltrate were semiquantitatively assessed in 25 breast tumors.

Results: The risk allele of rs2981578 was associated with increased FGFR2 mRNA levels in skin fibroblasts, but not in skin epithelial cell cultures. FGFR2 mRNA levels in skin fibroblasts and breast fibroblasts correlated strongly in the patients from whom both cultures were available. Tumor-derived fibroblasts expressed, on average, eight times more FGFR2 mRNA than the corresponding fibroblasts from normal breast tissue. Fibroblasts with higher FGFR2 mRNA expression showed more FRS2α and ERK1/2 phosphorylation after exposure to FGF2. In fibroblasts, higher FGFR2 expression correlated with higher FGF10 expression. In 25 breast tumors, no associations between breast tumor characteristics and fibroblast FGFR2 mRNA levels were found.

Conclusions: The influence of rs2981578 genotypes on FGFR2 mRNA expression levels is cell type-dependent. Expression differences correlated well with signaling levels of the FGFR2 pathway. Our results suggest that the increased breast cancer risk associated with SNP rs2981578 is due to increased FGFR2 signaling activity in stromal fibroblasts, possibly also involving paracrine FGF10 signaling.

Introduction

Several genome-wide association studies have shown that the minor allele of SNP rs2981582, located in intron 2 of the fibroblast growth factor receptor 2 gene (FGFR2), is associated with increased breast cancer risk [1-6]. The odds ratios (ORs) for this SNP are 1.23 in heterozygotes and 1.63 in homozygotes for the minor allele [1,2], but attributable risk is high because of the high frequency of the risk allele population. Fine-scale genetic mapping and resequencing of the region surrounding rs2981582 resulted in the identification of up to eight variants in a linkage disequilibrium block (LD block) within intron 2 of FGFR2 most strongly associated with increased breast cancer risk, including SNP rs2981578 [1,5,7]. The location of this LD block suggests that these variations somehow modify the functioning of FGFR2.
Meyer et al. [7] have shown that two SNPs within this LD block, one of them being rs2981578, alter the DNA binding affinity of octamer-binding transcription factor 1 (Oct-1), runt-related transcription factor 2 (Runx2) and CCAAT/enhancer binding protein β (C/EBPβ). Accordingly, increased expression of FGFR2 mRNA was observed in total RNA isolated from breast tumors of patients homozygous for the risk allele as compared to homozygotes for the major allele [7]. Paradoxically, Sun et al. [8] recently reported decreased expression of FGFR2 mRNA in normal breast tissue of homozygotes for the risk allele.

FGFR2 is one of five fibroblast growth factor (FGF) receptors known in humans to be involved in various signaling pathways that regulate processes such as cell growth, apoptosis and differentiation. Two isoforms, FGFR2-IIIb and FGFR2-IIIc, are the result of mutually exclusive alternative splicing of exon 9 or 10 of FGFR2. Isoform IIIb is present on epithelial cells and binds ligands FGF3, FGF7, FGF10 and FGF22 and isoform IIIc is present on mesenchymal cells and binds FGF2, FGF4, FGF6, FGF9, FGF17 and FGF18 [9]. Binding of a ligand to the receptor can activate several signaling pathways, including the mitogen-activated protein kinase (MAPK) pathway [10,11].

Downregulation of FGFR2 protein has been reported in up to 67% of breast tumors [12], whereas amplification of FGFR2 and upregulation of FGFR2 mRNA expression have been reported in less than 10% of breast tumors [10,13]. Somatic FGFR2 mutations are rare in breast cancer [14]. A switch from the IIIb to the IIIc isoform in tumor cells, resulting in activation of the receptor by other FGFs, has been reported in a subset of prostate cancers and in a few breast cancer cell lines [15-17].

To further unravel the mechanisms by which the SNPs in intron 2 of FGFR2 increase breast cancer risk, and to address the heterogeneous cellular composition of breast tumors, we studied the expression of FGFR2 mRNA in relation to the rs2981578 genotype in fibroblasts and epithelial cells cultured from breast tissue. We also compared the FGFR2 mRNA expression in fibroblasts derived from normal skin tissue, normal breast tissue and breast tumor tissue. Furthermore, we explored the functional implications of different levels of FGFR2 expression at the cellular level by studying the downstream MAPK pathway. Finally, we compared histological characteristics between tumors of patients with high and low FGFR2 levels.

Materials and methods

Patients
Breast tissue was obtained from 98 women who had undergone breast cancer-related surgery at the Leiden University Medical Center (LUMC) from February 2006 until December 2010 (patient demographics are given in Table 1). According to the Dutch Medical Treatment Act, anonymized samples obtained during medical treatment may be used in medical research if the patient does not object to this “secondary use” (opt-out system). Samples were coded in such a way that identifying information was not accessible by the researcher, but samples still could be linked to pathology reports by authorized clinicians. The use of residual material for this study was approved by the Department of Pathology of the LUMC (code OP 25-06). The study protocol was compliant with the Code of Conduct issued by the Dutch Federation of Medical Scientific Societies.

Tissue culture
Fibroblasts and epithelial cells were cultured separately from skin tissue, normal breast tissue or tumor tissue by cutting the tissue patches into 2-mm × 2-mm pieces. Tissue patches were allowed to attach to the culture flask for 30 minutes, then we added DMEM/F12 medium (1:1 dilution; GIBCO/Invitrogen, Breda, the Netherlands) supplemented with 20% FCS (Bodinco, Alkmaar, The Netherlands) and antibiotics. Cells were grown at 37°C in 5% CO₂. Each fibroblast culture was expanded in medium supplemented with 10% FCS and antibiotics. Epithelial cells were grown in HuMEC Ready Medium (GIBCO/Invitrogen) or in DermaLife K Serum-Free Keratinocyte Culture Medium (Lifeline Cell Technology, Walkersville, MD, USA) (see also Table 2). The morphology of primary cultures was in agreement with the morphology of established epithelial and mesenchymal cell lines (Figure S1 in Additional file 1).

Genotyping
Genomic DNA was isolated using the Wizard Genomic DNA Purification Kit (Promega, Leiden, The Netherlands) according to the manufacturer’s instructions. Four SNPs in intron 2 of FGFR2 were genotyped (Table 3).

Table 1 Characteristics of the patient cohort

| Characteristics               | Data                     |
|------------------------------|--------------------------|
| Total number of patients     | 98                       |
| BRCA1/2 mutation carriers, n (%) | 10 (10%)                |
| Diagnosis                    |                          |
| Mean age at diagnosisb, years (±SD) | 55 (±14)                |
| Invasive breast cancer, n     | 83                       |
| In situ breast cancer, n      | 8                        |
| Prophylactic surgery, no cancer, n | 7                     |
| Tumor characteristics (n = 91) |                          |
| ER status                    | 54 positive, 20 negative, 17 unknown |

*SD: standard deviation; ER: estrogen receptor. bAge at diagnosis of breast cancer.
Quantitative real-time PCR

Total RNA was isolated from exponentially growing fibroblasts or epithelial cells using NucleoSpin RNA II Kit (Clontech, St-Germain-en-Laye, France) according to the manufacturer’s instructions. During isolation, a 30-minute DNase treatment was performed to ensure complete degradation of contaminating DNA.

A detailed description of the RT reaction and quantitative PCR (qPCR) conditions can be found in the supplementary methods section (Additional file 2). Briefly, qPCR was performed to analyze the expression of a specific gene (Table 4) using the Bio-Rad iCycler thermal cycler and the iQ SYBR Green Supermix (Bio-Rad Laboratories, Hercules, CA, USA) according to the manufacturer’s recommendations. Each gene was measured at least twice in each sample. As reference genes, the TATA box binding protein (TBP) and heterogeneous nuclear ribonucleoprotein M (HNRPM or HNRNPM) (fibroblasts) genes or signal recognition particle receptor (SRPR), HNRPM and TBP (epithelial cells) genes were used.

Fragment analysis

Isoforms FGFR2-IIIb and FGFR2-IIIc differ by the alternative splicing in of either exon 9 or exon 10 into the mature mRNA, resulting in a difference of 3 bp in length of the mature mRNA. A PCR fragment of 297 bp for FGFR2-IIIb or 300 bp for FGFR2-IIIc mRNA was amplified by PCR with 38 cycles and an annealing temperature of 70°C using the 6-carboxyfluorescein-labeled forward primer 5’-GTGGAAAGAAGCGGACTAAA-TACG-3’ and reverse primer 5’-CACCATAAGGGC-GATTTAAGAGACC-3’ located in exons 8 and 11.

Fragment analysis was performed on cDNA from 14 skin epithelial cell cultures and 52 skin fibroblast cultures using the 3730xl DNA Analyzer (Applied Biosystems, Carlsbad, CA, USA) and the GeneScan 400HD ROX Size Standard (Applied Biosystems).

Measuring FGFR2 protein levels

FGFR2 protein levels were analyzed in seven exponentially growing fibroblast cultures with high (n = 3) or...
low (n = 4) FGFR2 mRNA levels. Total protein isolation and Western blot analysis are described in detail in the supplementary methods section (Additional file 2). Each sample was measured twice on separate gels. The primary and secondary antibodies used are given in Table 5. The Odyssey Infrared Imaging System and Odyssey 3.0 software (LI-COR Biotechnology, Cambridge, UK) were used to visualize and identify the bands.

**Analyzing the phosphorylation of downstream FGFR2 targets**

Five skin fibroblast cultures with high FGFR2 mRNA expression and five skin fibroblast cultures with low FGFR2 mRNA expression were randomly selected. In each experiment, one culture with high mRNA expression and one culture with low mRNA expression were compared. In each well of a six-well plate, 5 \times 10^5 fibroblasts from the full cell culture flasks were seeded and 10% FCS medium was added. The cells were allowed to attach to the well bottom for 24 hours and were then starved in 0.5% FCS medium for 12 hours. Cells were subsequently exposed to 0 or 20 ng of FGF2 (basic fibroblast growth factor, 9952; Cell Signaling Technology, Danvers, MA, USA) in 0.5 mL of 0.5% FCS medium for 10 minutes. This length of time was chosen because in an initial experiment phosphorylation levels peaked at about 10 minutes (Figure S2 in Additional file 3).

Total protein was then isolated, and Western blot analysis was performed to assess the phosphorylation of downstream targets of FGFR2 as described in more detail in the supplementary methods section (Additional file 2). The primary and secondary antibodies that were used are given in Table 5. Phosphorylation levels after 10 minutes of exposure were normalized to phosphorylation levels before exposure.

**Determining the stroma percentage within the primary tumor**

Routine H & E-stained histological tumor sections were obtained from the Department of Pathology for 50 of the 68 patients from whom skin fibroblast cultures were available. The stroma percentage within the primary tumor was estimated by two researchers as previously described [18].

**Immunohistochemistry**

For the immunohistochemical analyses, patients were selected for being either homozygous for the risk allele and having high FGFR2 mRNA expression (n = 11) or for being homozygous for the major allele and having

| Gene and (GeneID) | Sequence ID | Primer | Primer sequence (5' to 3') | Product length | Distance from poly(A) tail | Exon-exon boundary |
|------------------|-------------|--------|-----------------------------|----------------|--------------------------|-------------------|
| FGF2             | NM_0020064  | F      | ACCTGCAGACTGCTTTTGGCCA      | 91 bp          | 1,731 bp                 | No                |
| (2247)           |             | R      | GGTGCCACGTGAGAGCAGAGC       |                |                          |                   |
| FGF7             | NM_0020093  | F      | CTGAACGGCAATGCGGCTT          | 80 bp          | 1,170 bp                 | No                |
| (2252)           |             | R      | GCTTTCCAGGATTTGCTGACG        |                |                          |                   |
| FGF10            | NM_0044651  | F      | TCTTCTCTCTCTTCTTCTCCT       | 148 bp         | 325 bp                   | No                |
| (2255)           |             | R      | TCCCGGTCGACCTCCGCTTCGTC     |                |                          |                   |
| FGFR2             | NM_0001414  | F      | GTCACTGAGAAACATGAAACAGG     | 192 bp         | 3,368 bp                 | Yes               |
| (2263)           |             | R      | GTAGCTTCCAAATGCCAGTG         |                |                          |                   |
| GADPH            | NM_0020463  | F      | TTCCAGGAGCGAGATCCCT          | 175 bp         | 805 bp                   | Yes               |
| (2597)           |             | R      | CACCCATGAGCAACATGGG          |                |                          |                   |
| HMB5             | NM_0001903  | F      | CTGGTAACCGCAATGCGGCT         | 338 bp         | 1,010 bp                 | Yes               |
| (3145)           |             | R      | GCAGATGCG-CTCGATGGTA         |                |                          |                   |
| HNRPM            | NM_0059683  | F      | GAGGCCATGCTCTGGG             | 85 bp          | 440 bp                   | Yes               |
| (4670)           |             | R      | TTTCGATCTCCTGATGGTGA         |                |                          |                   |
| HPRT1            | NM_0001942  | F      | TGCACCTGCCAAGACATGCA         | 94 bp          | 742 bp                   | Yes               |
| (3251)           |             | R      | GTGGCTTTCTACCCAGCAAACCT      |                |                          |                   |
| SRPR             | NM_0031392  | F      | CATTGCGTTTGGACAGTAACCAA      | 70 bp          | 1,308 bp                 | Yes               |
| (6734)           |             | R      | ATTGTCTTCCATGCCGCCC          |                |                          |                   |
| TBP              | NM_0031943  | F      | CACCGAACCAGCGACGATT          | 89 bp          | 905 bp                   | Yes               |
| (6908)           |             | R      | TTTTGCTGCTGAGCAGTCGAGC       |                |                          |                   |

**Table 4 Primers used during real-time PCR analyses**

- **FGF**: fibroblast growth factor gene; **FGFR**: fibroblast growth factor receptor gene; **GAPDH**: glyceraldehyde 3-phosphate dehydrogenase gene; **HMB5**: hydroxymethylbilane synthase gene; **HNRPM**: heterogeneous nuclear ribonucleoprotein M gene; **HPRT1**: hypoxanthine phosphoribosyltransferase 1 gene; **SRPR**: signal recognition particle receptor gene; **TBP**: TATA box binding protein gene; F: forward primer; R: reverse primer; bp: base pair. For each gene, the forward and reverse primer sequences, the length of the resulting PCR product (using cDNA as template) and the distance from the poly(A) tail are shown, as is the information about whether the PCR product includes an exon-exon boundary. **GeneID** from EntrezGene accessed 2 June 2010. **Distance from 3' end of the PCR product to 5' beginning of the poly(A) tail.** **Primer set for FGFR2 is in a region of FGFR2 that is present in both FGFR2 IIIb and FGFR2 IIIc.**
Table 5 Antibodies used during Western blot analyses\(^a\)

| Antigen targeted | Antibody (catalog number, manufacturer) | Clonality | Dilution | Origin |
|------------------|----------------------------------------|-----------|----------|--------|
| Primary antibodies | FGFR2 | Bek C-17 (sc-122, SZ) | Polyclonal | 1 in 500 | Rabbit |
| \(\alpha\)-tubulin | Anti-\(\alpha\)-tubulin (T6199, SA) | Monoclonal | 1 in 8,000 | Mouse |
| ERK1/2 | p44/p42 MAPK antibody (9102, CS) | Polyclonal | 1 in 100 | Rabbit |
| Phosphorylated ERK1/2 | Phospho-p44/p42 MAPK antibody (4377, CS) | Monoclonal | 1 in 200 | Rabbit |
| FRS2\(\alpha\) | FRS2 H-91 (sc-8318, SZ) | Polyclonal | 1 in 50 | Rabbit |
| Phosphorylated FRS2\(\alpha\) | Phospho-FRS2-\(\alpha\) antibody (3864, CS) | Polyclonal | 1 in 50 | Rabbit |
| Secondary antibodies | Mouse IgG | IRDye 680 anti-mouse IgG (926-32220, LC) | Polyclonal | 1 in 7,500 | Goat |
| Rabbit IgG | IRDye 800 anti-rabbit IgG (926-32211, LC) | Polyclonal | 1 in 5,000 | Goat |

\(^a\)FGFR2: fibroblast growth factor receptor 2 gene; ERK1/2: extracellular signal-regulated kinases 1 and 2; FRS2\(\alpha\): fibroblast growth factor receptor substrate 2\(\alpha\); IgG: immunoglobulin G; MAPK: mitogen-activated protein kinase. Manufacturer names are abbreviated as follows: SZ: Santa Cruz Biotechnology, Santa Cruz, CA, USA; SA: Sigma-Aldrich, Zwijndrecht, The Netherlands; CS: Cell Signaling Technology, Danvers, MA, USA; LC, LI-COR Biosciences, Cambridge, UK. For each antibody, the target, manufacturer, clonality, dilution used during Western blot analysis and origin are given.

Statistical analysis

The distribution of the SNP genotypes was studied using an Excel-based Hardy-Weinberg equilibrium (HWE) calculator [20]. For all other statistical analyses, we used PASW Statistics version 17.0 software (SPSS Inc., Nieuwegein, The Netherlands).

Results

A total of 68 skin fibroblast cultures, 44 breast fibroblast cultures, 11 tumor-derived fibroblast cultures and 25 skin epithelial cell cultures were established from 98 patients who had undergone breast cancer-related surgery at LUMC. We genotyped four SNPs in intron 2 of FGFR2 (Table 6). All SNPs were in HWE. SNP rs2981578 was chosen to represent all four SNPs because of its reported effect on the binding of transcription factor Runx2 and because it showed strong LD with the other three SNPs including rs2981582.

FGFR2 mRNA expression in fibroblasts and epithelial cells

A significant correlation between the rs2981578 genotype and FGFR2 mRNA expression level as measured by qRT-PCR was present in the 68 skin fibroblast cultures (Figure 1A) \((P = 0.02\); one-way analysis of variance (ANOVA)). Although expression levels varied widely within each genotype group, a dosage-dependent effect was seen, with the highest average expression found among homozygotes for the minor allele (the risk allele), followed by heterozygotes, and the lowest average expression found among homozygotes for the major allele. In contrast, among 25 skin epithelial cell cultures, there were no statistically significant differences in FGFR2 mRNA expression levels between the three genotype groups, although the average levels of FGFR2 mRNA were slightly lower in carriers of one or two copies of the risk allele (Figure 1B) \((P = 0.732\); one-way ANOVA).

Table 6 Genotype distribution of four SNPs in FGFR2\(^a\)

| Genotype | Number of patients |
|----------|-------------------|
| CT       | AG                | AG | CT | 29 |
| TT       | GG                | GG | CC | 22 |
| CC       | AA                | AA | TT | 21 |
| CT       | GG                | GG | CC | 7  |
| CC       | AG                | AG | CT | 5  |
| TT       | AA                | AA | TT | 1  |

\(^a\)FGFR2: fibroblast growth factor receptor 2 gene. The number of patients who carry each combination of the four genotypes is shown in the right-hand column. Although we do not have haplotype information, the genotype distribution shows the strong linkage disequilibrium present within this region. The alleles associated with increased breast cancer risk are rs2981582: T; rs2981578: G; rs10736303: G; and rs7895676: C. \(^b\)For the remaining 13 patients, only rs2981578 was genotyped; of these patients, 5 carried AA, 5 carried AG and 3 carried GG.
FGFR2 mRNA expression in fibroblasts derived from different tissues

To address whether FGFR2 expression levels in skin fibroblasts correlated to those in breast fibroblasts, we cultured fibroblasts from the skin tissue as well as the normal breast tissue from 22 breast cancer patients. There was a significant correlation between the FGFR2 mRNA levels in the skin fibroblasts and the breast fibroblasts (Figure 2A) (Pearson’s correlation coefficient = 0.64, \( P = 0.001 \)). Expression levels were on average 2.8 times higher in the breast fibroblasts than in the skin fibroblasts (\( P = 0.001 \); paired t-test).

For 11 of these 22 patients, we also successfully grew fibroblasts from the tumor tissue. FGFR2 mRNA expression in tumor-derived fibroblasts was on average eight times higher than in breast fibroblasts and sixteen times higher than in skin fibroblasts (Figure 2B) (\( P = 3 \times 10^{-4} \) and \( P = 2 \times 10^{-4} \), respectively; paired t-tests).
**FGFR2 mRNA isoform expression analysis in fibroblasts and epithelial cells**

Since an isoform switch from FGFR2 IIIb to FGFR2 IIIc has been reported in a few breast cancer cell lines, and since this switch may contribute to tumor development, we explored whether rs2981578 genotype influences the alternative splicing of isoforms of FGFR2. The expected FGFR2-IIIb was detected in 14 epithelial cell cultures, and the expected FGFR2-IIIc was detected in 48 of 52 fibroblast cultures. In the remaining four fibroblast samples, FGFR2-IIIb was present at a level approximately 10% of that of FGFR2-IIIc, but the presence or absence of FGFR2-IIIb was not associated with rs2981578 genotype ($P = 0.32$; Pearson’s $\chi^2$ test).

**Correlation between FGFR2 and FGF10 mRNA expression**

To explore a possible paracrine relationship between fibroblasts and epithelial cells, the mRNA expression levels of FGF2, FGF7 and FGF10 were measured in the 68 skin fibroblast cultures and compared to their FGFR2 mRNA expression. FGF2 mRNA expression was not correlated with FGFR2 expression (Figure 3C) (Pearson’s correlation coefficient = 0.22, $P = 0.07$). The correlation between FGFR2 and FGF7 mRNA levels in skin fibroblasts did not remain significant after correction for multiple testing (Figure 3B) (Pearson’s correlation coefficient = 0.28, $P = 0.02$).

FGFR2 and FGF10 expression levels were loosely but significantly correlated in the skin fibroblast cultures (Figure 3A) (Pearson’s correlation coefficient = 0.60, $P = 8 \times 10^{-8}$). There was also a suggestive correlation between FGF10 expression and rs2981578 genotype in these cultures ($P = 0.06$; one-way ANOVA) (Figure S3 in Additional file 4). In 44 fibroblast cultures from normal breast tissue, there was a suggestive correlation between FGFR2 and FGF10 mRNA levels (Spearman’s $\rho = 0.25$, $P = 0.11$) (Figure S4 in Additional file 5).

**FGFR2 protein expression**

In seven fibroblast cultures, FGFR2 protein levels were quantified by Western blot analysis and compared with the FGFR2 mRNA levels. The FGFR2 antibody that was used detected a full-length FGFR2 recombinant protein, but absolute protein expression levels in fibroblasts were very low, giving poor signal-to-noise ratios. Possibly as a result of this, we were unable to demonstrate a correlation between FGFR2 mRNA and protein levels (Spearman’s $\rho = -0.14$, $P = 0.76$) (Figure S5 in Additional file 6).

**Phosphorylation of downstream FGFR2 targets**

To investigate whether the differences in FGFR2 mRNA expression levels correspond with different levels of FGFR2 pathway activity, we compared the phosphorylation of downstream targets FGF receptor substrate 2a...
Phosphorylation of FRS2α was measured in four fibroblast cultures, two with high and two with low FGFR2 expression. The sample with higher FGFR2 expression showed a larger increase in phosphorylation of FRS2α after FG2 was added compared to the sample with lower FGFR2 expression (Figure 4) ($P = 0.18$; Wilcoxon signed-rank test).

Phosphorylation of ERK1/2 increased in all skin fibroblast cultures after exposure to FG2, and this effect was again more pronounced in the sample with higher FGFR2 expression in all five experiments (Figure 4) ($P = 0.04$; Wilcoxon signed-rank test).

**FGFR2 mRNA level and histological breast tumor characteristics**

We explored tumor parameters in patients with different FGFR2 mRNA levels in their fibroblasts. Since the percentage of stroma in the primary tumor may vary considerably [18] and FGFR2 signaling in the stroma could influence cell proliferation, we explored whether patients with higher FGFR2 mRNA expression in fibroblasts had a higher stroma percentage. In the 50 patients analyzed, no correlation was present between FGFR2 mRNA levels in their fibroblasts and the percentage of stroma within the tumor (Spearman’s $\rho = 0.17$, $P = 0.23$). Unfortunately, not enough tumor tissue was available from patients from whom we had obtained skin epithelial cells.

Because FGF signaling in cancer has been associated with induction of angiogenesis and lymphocytic infiltration [21], the number of microvessels was determined and T-cell infiltrate was quantified in breast tumors from patients whose fibroblasts had relatively high ($n = 11$) or relatively low ($n = 14$) FGFR2 expression. Interobserver agreement regarding the number of blood vessels per HPF was high (Pearson’s correlation coefficient $= 0.89$, $P = 1 \times 10^{-5}$), but no correlation with FGFR2 mRNA levels was present (Pearson’s correlation coefficient $= 0.04$, $P = 0.86$). No correlations between the amount of T-cell infiltrate and FGFR2 mRNA levels in the fibroblasts were detected either (T cells in stroma: Pearson’s correlation coefficient $= 0.04$, $P = 0.86$; T cells in tumor: Pearson’s correlation coefficient $= 0.15$, $P = 0.52$).

Finally, since the SNPs in intron 2 of FGFR2 are mainly associated with estrogen receptor-positive (ER-positive) breast tumors [1,22], we studied a possible correlation between FGFR2 mRNA levels and ER status of the tumor in 50 patients, but could detect none ($P = 0.60$; logistic regression).

**Discussion**

Aberrant FGF signaling has been implicated in the pathogenesis of multiple types of cancer, including breast cancer [11,23]. Germline genetic variation in an LD region within intron 2 of FGFR2 has been associated with a modestly increased breast cancer risk. Fine-scale genetic mapping and functional analyses identified up to eight SNPs, including SNP rs2981578, as likely causal variants [1,5,7]. It was demonstrated that these SNPs influence mRNA expression levels of the FGFR2 gene. Despite this progress, substantial uncertainty remains regarding how subtle modulation of FGFR2 expression levels may modify breast cancer risk. In addition, opposite effects of intron 2 SNP genotypes on FGFR2 mRNA expression have been reported in tumor tissue and normal breast tissue [7,8].

We found, on average, higher FGFR2 mRNA levels in skin fibroblast cultures of heterozygotes and homozygotes for the risk allele of SNP rs2981578 relative to homozygotes for the major allele. This is in agreement with measurements of FGFR2 mRNA expression in total RNA from breast tumor tissue [7]. However, no effect of genotype was observed in our skin epithelial cell cultures. Also, epithelial breast tumor cells express lower levels of FGFR2 than surrounding normal breast...
epithelium [12]. Soluble factors secreted or recruited by tumor cells may induce expression changes in neighboring normal cells, leading to gene expression differences between tumor-derived stromal fibroblasts and normal breast stroma [24]. In the 11 patients from whom we obtained fibroblasts from skin, normal breast tissue and breast tumor tissue, FGFR2 expression levels in the tumor-derived fibroblasts were consistently higher than in the fibroblasts from normal breast tissue. A similar finding was made recently in cell cultures from patients with esophageal cancer [25]. Unfortunately, our sample set was too small to conclusively establish whether expression levels of FGFR2 mRNA in tumor-derived fibroblasts are similarly associated with SNP genotypes in intron 2 as they are in skin-derived fibroblasts. Taken together, however, these data suggest that the association between genotype and FGFR2 expression observed by Meyer et al. [7] in total breast tumor homogenates was derived from cancer-associated fibroblasts rather than from the tumor (or epithelial) component. Because the transcription factors Oct-1/Runx2 and C/EBPβ display differential binding to these SNP alleles in epithelial breast tumor cells, it will be interesting to study this in other cell types constituting breast tumor stroma.

Our results in fibroblast and epithelial cell cultures are at odds with those obtained by Sun et al. [8], who reported lower FGFR2 mRNA expression in normal breast tissue from homozygotes for the risk allele. However, the differences reported by Sun et al. were small and the correlation was weak. In our epithelial cell cultures, there was a trend toward lower FGFR2 mRNA expression in carriers of one or two copies of the risk allele, but the differences were very small. The insufficient statistical power of our studies or the differences in experimental design (whole tissue analysis versus analysis of cultured epithelial cells) may underlie these different outcomes.

The variation in FGFR2 mRNA expression between individuals with the same intron 2 genotype is wide in both fibroblasts and epithelial cells. Apparently, the causal variants in intron 2 of FGFR2 only partly determine the FGFR2 mRNA expression level. We have shown that in skin fibroblasts, higher FGFR2 mRNA levels correspond to higher activity of the FGFR2 pathway upon stimulation by ligand FGF2, indicating that the allelic status of the intron 2 SNPs is functional at the FGF signaling level. Cells with higher FGFR2 expression probably respond differently to the same fibroblast growth factor concentration in their microenvironment [26]. Thus, the overall activity of the FGFR2 pathway might be a more accurate predictor of breast cancer risk than rs2981578 or rs2981582 genotype status, although it is presently unclear through which cell type and in which developmental phase of the mammary gland this activity contributes most to this risk.

Fibroblasts have a well-recognized role in the carcinogenic process as remodelers of the extracellular matrix in tumor stroma and as a source of paracrine growth factors that influence the growth of carcinoma cells [27,28]. Unequivocal evidence that paracrine FGF released from breast tumor stroma functions to promote tumorigenesis is lacking, but, intriguingly, we found a strong correlation between FGFR2 and FGF10 mRNA expression levels in the cultured skin fibroblasts. We have not investigated the mechanism underlying this correlation, nor have we been able to establish that it also holds true for tumor-derived fibroblasts. Since FGF10 is known to be secreted by fibroblasts and to bind specifically to the FGFR2-IIIb isoform expressed on epithelial cells, however, our findings would fit a model of paracrine tumor-stroma interaction. The FGFR2-IIIb-FGF10 interaction plays a key role in the normal embryological and postnatal development of the mammary glands in mice [29,30]. Mice deficient in Fgf10 or Fgfr2b fail to develop normal mammary glands. Apparently, Fgfr2b signaling is crucial for the survival and proliferation of the mammary luminal epithelial cells but does not affect the regenerative potential of the mammary epithelial progenitor cells. Fgf10 overexpression in the stromal compartment of the murine prostate results in epithelial cell hyperproliferation [31]. Also, in humans, FGF10 is thought to stimulate epithelial cell proliferation [32].

Thus, it is conceivable that, in the human breast, slightly increased levels of FGFR2 and FGF10 result in a slightly increased ductal branching. If this primarily involved the luminal epithelial component of the breast tissue as it does in mice, this would explain why the increased breast cancer risk conferred by FGFR2 intron 2 SNPs is mostly restricted to ER-positive tumors [22,33]. High FGF2 and/or FGFR2 protein levels have been correlated with high ER levels in breast cancer [34,35]. Our cohort was probably underpowered to demonstrate a correlation between ER status of the tumor and FGFR2 mRNA expression levels in skin fibroblasts. FGF7, also secreted by breast fibroblasts, has similarly been suggested to act as a paracrine growth factor in human breast cancer [36], but our data do not demonstrate a significant link between FGF7 and FGFR2 expression.

In pancreatic cancer, FGF10 is found in stromal cells, close to the tumor cells, and is thought to interact with FGFR2-IIIb on the tumor cells, thereby inducing cell migration and invasion [37]. Since the downstream effects of activation of FGFR2 by different FGFs in different cell types are very diverse and could include apoptosis, cell proliferation and angiogenesis [11], it is difficult to predict which of these effects could mechanistically explain the increased breast cancer risk.
associated with intron 2 SNPs. Here we have explored some of the end points of these processes in breast tumors from patients with different FGFR2 mRNA levels in their fibroblasts. Tsunoda et al. [38] reported increased T-lymphocyte and macrophage infiltration into a newly inoculated tumor when they injected FGF2 into this tumor. In mice, overexpression of Fgf10 leads to highly vascularized tumors in immunocompetent mice [39]. However, we found no correlation between FGFR2 mRNA levels and, respectively, stroma percentage of the tumor, microvessel density and T-cell infiltrate. Our sample size may have been too small to detect any existing differences, in particular because these differences can be expected to be small, given the mildly increased breast cancer risks conferred by FGFR2 SNPs.

A limitation of our study is that our observations were based on cultured cells from surgically removed tissues. Culture conditions between fibroblasts and epithelial cells were necessarily different and may have influenced some of our findings, but this enabled us to study RNA expression levels by cell type instead of by heterogeneous tissue. It has long been known that the phenotype of fibroblasts can differ depending on anatomical site [40-43]. Indeed, we did observe absolute differences in FGFR2 mRNA expression levels between fibroblasts from skin tissue and those from normal breast tissue, but we demonstrated that these correlate very well (Figure 2).

Conclusions
In conclusion, it is likely that the causative variants tagged by rs2981578 in intron 2 of the FGFR2 gene cause a higher breast cancer risk by influencing FGFR2 expression levels. Here we have shown that the effect of intron 2 SNPs on FGFR2 expression is cell type-specific. Different effects were observed in skin fibroblasts and epithelial cells. Tissue specificity for expression quantitative trait loci is common [44] and clearly also applies to FGFR2.

In addition, we observed differences in the levels of FGFR2 mRNA expression between fibroblasts derived from normal breast tissue or from tumor tissue, which strongly supports a holistic model to explain FGFR2-related breast cancer risk [45] rather than one assuming cell autonomous effects of FGFR2 expression modulation. Our finding that individuals in whom intrinsically higher levels of FGFR2 are expressed in their skin fibroblasts also have higher levels of FGF10 suggests that the increased breast cancer risk might be due to a stronger paracrine effect between stromal and tumor cells involving FGF10 signaling. The fact that the association between FGFR2 and FGF10 expression was not observed by Meyer et al. [7] in 45 normal breast tissue samples underscores the importance of analyzing the various constituting cell types separately in sufficiently large cohorts. Since we limited our search for such associations to FGFs secreted by fibroblasts, and given that the FGFR2 and FGF10 genes are located on different chromosomes, it will be important to extend these analyses to genome-wide expression differences between different cell types in various FGFR2 genotype backgrounds.

Additional material

Additional file 1: Figure S1 (A) Typical fibroblast and (B) typical epithelial cell cultures (original magnification, ×10).

Additional file 2: Supplementary methods. This file contains supplementary methods regarding the quantitative real-time PCR and Western blot analyses.

Additional file 3: Figure S2 Phosphorylation levels of downstream targets of FGFR2 after different periods of stimulation with FGF2 in one fibroblast sample (sample from experiment 1 with high FGFR2 mRNA levels). (A) Using one of the blots as an example, we show phosphorylated ERK1/2 examined after 0, 1, 5, 10 and 20 minutes. H: lanes with total protein from a fibroblast sample with high FGFR2 mRNA level; L: lanes from a fibroblast sample with low FGFR2 mRNA level; M: lane with the length marker; T: tubulin, E1/2: ERK1/2. (B) Phosphorylation levels of FRS2α, ERK1 and ERK2 are shown as fold increases compared to the phosphorylation levels at 0 minutes of stimulation.

Additional file 4: Figure S3 The relationship between FGF10 mRNA expression and the rs2981578 genotype in 68 skin fibroblast cultures (P = 0.06; one-way ANOVA). The expression levels were log₂-transformed and normalized to HNRPM and TBP expression.

Additional file 5: Figure S4 Correlation of expression levels of FGFR2 and FGF10 mRNA in 44 breast fibroblast cultures. FGFR2 and FGF10 expression levels were normalized to HNRPM and TBP and log₂-transformed. Each dot represents the expression levels of one patient (Spearman’s ρ = 0.25, P = 0.11).

Additional file 6: Figure S5 Western blot analysis measuring FGFR2 protein levels in fibroblasts. (A) Western blot showing results for seven different fibroblast cultures. H: lanes with total protein from fibroblasts with high FGFR2 mRNA levels; L: lanes with total protein from fibroblasts with low FGFR2 mRNA levels; empty: empty lane; M: lane with length marker, recomb: lane with pure recombinant FGFR2. (B) FGFR2 mRNA levels and FGFR2 protein levels in the seven fibroblast samples. The FGFR2 mRNA results were normalized to HNRPM and TBP and log₂-transformed. The FGFR2 protein results were normalized to α-tubulin. Each dot represents the results for one fibroblast sample.

Abbreviations
bp: base pairs; C/EBPβ: CCAAT/enhancer binding protein β; CI: confidence interval; ER: estrogen receptor; Erk1/2: extracellular signal-regulated kinases 1 and 2; FCS: fetal calf serum; FGFR2: fibroblast growth factor receptor 2 gene; FGF: fibroblast growth factor; FRS2α: fibroblast growth factor receptor substrate 2α; H & E: hematoxylin and eosin; HNRPM: heterogeneous nuclear ribonucleoprotein M; HPF: high-power field; HWE: Hardy-Weinberg equilibrium; LD: linkage disequilibrium; MAPK: mitogen-activated protein kinase; Oct-1: octamer-binding transcription factor 1; OR: odds ratio; PCR: polymerase chain reaction; qPCR: quantitative real-time PCR; Runx2: runt-related transcription factor 2; SNP: single-nucleotide polymorphism; SNP: signal recognition particle receptor; TBP: TATA box binding protein.

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Authors’ contributions
The experiments were performed by PH, MD, MG and AM. The patient material was provided by RT and VS. The cells were cultured by FB and MV. The stroma percentage of 50 tumors was calculated by EB and WM. The experiments were designed, analyzed and interpreted by PH, CA and PD. EZ helped with the statistical analyses and the interpretation of the data. The manuscript was drafted by PH and critically revised by MV, CA and PD. All authors read and approved the final manuscript.

Competing interests
The authors declare that they have no competing interests.

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References
1. Easton DF, Pooley KA, Dunning AM, Pharoah PD, Thompson D, Ballinger DG, Struwing JP, Morrison J, Field H, Luben R, Wareham N, Ahmed S, Healey CS, Bowman R, SEARCH collaborators, Meyer KB, Haiman CA, Kolonel LK, Henderson BE, Le Marchand L, Brennan P, Sangrajrang S, Gaborineau V, Odeffrey F, Shen CY, Wu PE, Wang HC, Eccles D, Evans DG, et al. Genomic-wide association study identifies novel breast cancer susceptibility loci. Nature 2007, 447:1087-1092.
2. Hunter DJ, Kraft P, Jacobs KB, Cox DG, Yeager M, Hankinson SE, Wacholder S, Wang Z, Welch R, Hutchinson A, Wang J, Yu K, Chattejee N, Orr N, Willett WC, Colditz GA, Rieger RG, Berg CD, Buys SS, McCarron CY, Flegelson HS, Calle EE, Thun MJ, Hayes RB, Tucker M, Gerhard DS, Fraumeni JP, Jr, Hoover RN, Thomas G, Chanock SJ. A genome-wide association study identifies alleles in FGF2 associated with risk of sporadic postmenopausal breast cancer. Nat Genet 2007, 39:870-874.
3. Kawase T, Matsuo K, Suzuki T, Hiraki A, Watanabe M, Ivata H, Tanaka H, Tajima K. FGF2 intron polymorphisms interact with reproductive risk factors of breast cancer: results of a case control study in Japan. Int J Cancer 2009, 125:1946-1952.
4. Liang J, Chen P, Hu Z, Zhou X, Chen L, Li M, Wang Y, Tang J, Wang H, Shun H. Genetic variants in fibroblast growth factor receptor 2 (FGFR2) contribute to susceptibility of breast cancer in Chinese women. Carcinogenesis 2008, 29:2341-2346.
5. Udler MS, Meyer KB, Pooley KA, Karlins E, Struwing JP, Zhang J, Doody DR, MacArthur S, Tyer J, Pharoah PD, Loben R, Bernstein L, Kolonel LN, Henderson BE, Le Marchand L, Ursin G, Press MF, Brennam P, Sangrajrang S, Gaborineau V, Odeffrey F, Shen CY, Wu PE, Wang HC, Kang D, Yoo KY, Noh DY, Ahn SH, Ponder BA, Haiman CA, SEARCH collaborators. FGFR2 variants and breast cancer risk: fine-scale mapping using African American studies and analysis of chromatin conformation. Hum Mol Genet 2009, 18:1692-1703.
6. Zheng W, Cai Q, Signorello LB, Long J, Hargreaves MK, Deming SL, Li G, Li C, Cui Y, Blot WJ. Evaluation of 11 breast cancer susceptibility loci in African-American women. Cancer Epidemiol Biomarkers Prev 2009, 18:2761-2764.
7. Meyer KB, Maia AT, O’Reilly M, Teschendorff AE, Chin SF, Caldas C, Ponder BA. Allele-specific up-regulation of FGF2R increases susceptibility to breast cancer. PLoS Biol 2008, 6:e118.
8. Zheng W, Cui Y, Olopade OI, D’Errico RA. rs2081582 is associated with FGF2R expression in normal breast. Cancer Genet CytoGenet 2010, 197:193-194.
9. Esvarakumar VP, Lax I, Schlesinger J. Cellular signaling by fibroblast growth factor receptors. Cytokine Growth Factor Rev 2005, 16:139-149.
10. Knights V, Cook SJ. De-regulated FGF receptors as therapeutic targets in cancer. Pharmacol Ther 2010, 125:105-117.
11. Turner N, Grose R. Fibroblast growth factor factor signalling: from development to cancer. Nat Rev Cancer 2010, 10:116-129.
12. Zhang X, Zha SL, Ezzat S. Genetic and epigenetic mechanisms downstream of FGF receptor 2 to induce melanoma-associated antigen A in breast cancer. Am J Pathol 2010, 176:2333-2343.
13. Penaual-Llora F, Bertucci F, Adalid J, Parc P, Coulier F, Jacquemier J, Birnbaum D, deLapeyrière O. Expression of FGF2 and FGF receptor genes in human breast cancer. Int J Cancer 1995, 61:170-176.
14. Stephens P, Edkins S, Davies H, Greaves M, Cox C, Hunter C, Bignell G, Teague J, Smith R, Stevens C, O’Maya S, Parker A, Tarpey P, Avis T, Barbori B, Avren B, Bigg A, Bickel R, Atkinson L, Hunter C, Dicks E, Edwards K, Forbes S, Gorton M, Gray K, Halliday K, Harrison R, Hills K, Hinton J, Jones D, et al. A screen of the complete protein kinase gene family identifies diverse patterns of somatic mutations in human breast cancer. Nat Genet 2005, 37:590-592.
15. Swabi-Addo B, Kripluk F, Giri D, Ittmann M. Alternative splicing of fibroblast growth factor receptors in human prostate cancer. Prostate 2001, 46:163-172.
16. Luzumani BA, Bansal G, Mortimer C, Bulvuela L, Coombes RC. Expression of FGF2 BEK and K-SAM mRNA variants in normal and malignant human breast. Eur J Cancer 1996, 32A:518-524.
17. Zhu X, Asa SL, Ezzat S. Histone-acetylated control of fibroblast growth factor receptor 2 intron 2 polymorphisms and isoform splicing in breast cancer. Mol Endocrinol 2009, 23:1397-1405.
18. de Krijf EM, van Nes JG, van de Velde CJ, Putter H, Smit VT, Luiten A. FGF2 C terminus splice forms are differentially expressed in breast cancer. J Pathol 2008, 215:439-445.
19. Fung-Wong BD, Rupert K, Giri D, Ittmann M. Possible role of FGF2 isoforms in breast cancer. Breast Cancer Res Treat 2011, 125:687-696.
20. Ruffino AC, Johnston DA. Quantification of histochemical staining by color deconvolution. Anal Quant Cytol Histol 2001, 23:291-299.
21. Court lab HW calculator. (http://www.tuftsa.edu/~mcourt01/Documents/ Court%20lab%20calculator.pdf).
22. Acenova OD, Ittmann M, Spencer DM. Paths of FGF-driven tumorigenesis. Cell Cycle 2009, 8:580-588.
23. Garcia-Closas M, Hall P, Nevanlinna H, Pooley K, Morrison J, Richesson DA, Bojesen SE, Nordestgaard BG, Axelson CK, Arias JI, Milne RL, Ribas G, Gonzalez-Neira A, Benitez J, Zamora P, Brauch H, Justenhoven C, Hamann U, Ko YD, Brunnig T, Haas S, Dirk T, Schirrmann P, Hillemanns P, Bogdanov N, Brenner M, Karstens JH, Fagerholm R, Nalden K, Attomaki K, et al. Heterogeneity of breast cancer associations with five susceptibility loci by clinical and pathological characteristics. PloS Genet 2008, 4:e1000054.
24. Katoch M. Cancer genomics and genetics of FGFR2. Int J Oncol 2008, 33:233-237.
25. Singer CF, Gschwantler-Kaulich D, Fink-Retter A, Haas C, Hledustel G, Czarvenka K, Kubista E. Differential gene expression profile in breast cancer-derived stromal fibroblasts. Breast Cancer Res Treat 2008, 110:273-281.
26. Zhang C, Fu L, Fu J, Hu L, Yang H, Rong TH, Li Y, Liu H, Su SB, Zeng YK, Guan XY. Fibroblast growth factor receptor 2 positive fibroblasts provide a suitable microenvironment for tumor development and progression in esophageal carcinoma. Clin Cancer Res 2009, 15:4017-4027.
27. Garcia-Maya M, Anderson KA, Kendal CE, Kenny AV, Edwards-Ingram LC, Holladay A, Saffell JL. Ligand concentration is a driver of divergent signaling and pleiotropic cellular responses to FGF. J Cell Physiol 2006, 206:386-393.
28. Browwick NA, Neillson EG, Mosley HL. Stromal fibroblasts in cancer initiation and progression. Nat Rev 2004, 432:332-337.
29. Kalluri R, Zeisberg M. Fibroblasts in cancer. Nat Rev Cancer 2006, 6:392-401.
30. Mailleux AA, Spencer-Dene B, Dillon C, Ndiaye D, Savona-Baron C, Ittmann M, Teschendorff AE, Chin SF, Caldas C, Ponder BA, Solcia E, Bellusci S. Role of FGF10/FGFR2b signaling during mammary gland development in the mouse embryo. Development 2002, 129:1531-1540.
31. Pasa S, Ramasamy SK, De Langhe S, Gupte W, Haigh JJ, Medina D, Bellusci S. Terminal end bud maintenance in mammary gland is dependent upon FGFR2b signaling. Dev Biol 2008, 317:121-131.
32. Abate-Shen C, Shen MM. FGF signaling in prostate tumorigenesis: new insights into epithelial-stromal interactions. Cancer Cell 2007, 12:495-497.
32. Katoh M, Katoh M: FGFR2 and WDR11 are neighboring oncogene and tumor suppressor gene on human chromosome 10q26. Int J Oncol 2003, 22:1155-1159.

33. Stacey SN, Manolescu A, Sulem P, Thorlacius S, Gudjonsson SA, Jonsson GF, Jakobidottir M, Berghorsson JT, Gudmundsson J, Aben K, Strobbe LJ, Swinkels DW, van Engelenburg KC, Henderson BE, Kolonel LN, Le Marchand E, Ases B, Saez B, Lambea J, Godino J, Polo E, Tres A, Picelli S, Rantal a J, Margolin S, Jonsson T, Sigurdsson H, Jonasdottir T, Hafnielsson J, et al: Common variants on chromosome 5p12 confer susceptibility to estrogen receptor-positive breast cancer. Nat Genet 2008, 40:703-706.

34. Smith K, Fox SB, Whitehouse R, Taylor M, Greenall M, Clarke J, Harris AL: Upregulation of basic fibroblast growth factor in breast carcinoma and its relationship to vascular density, oestrogen receptor, epidermal growth factor receptor and survival. Ann Oncol 1999, 10:707-713.

35. Tuzlu S, Graault I, Vacher S, Vendrell J, Andreu C, Spyridis F, Cohen P, Lidereau R, Beche R: Identification of novel genes that co-cluster with estrogen receptor α in breast tumor biopsy specimens, using a large-scale real-time reverse transcription-PCR approach. Endocr Relat Cancer 2006, 13:1109-1120.

36. Hishikawa Y, Tamaru N, Ejima K, Hayashi T, Koji T: Expression of keratinocyte growth factor and its receptor in human breast cancer: its inhibitory role in the induction of apoptosis possibly through the overexpression of Bcl-2. Arch Histol Cytol 2004, 67:455-464.

37. Nomura S, Yoshimoto H, Takano S, Shida T, Kobayashi S, Ohtsuka M, Kimura F, Shimizu H, Yoshidome H, Kato A, Miyazaki M: FGF10/FGFR2 signal induces cell migration and invasion in pancreatic cancer. Br J Cancer 2008, 99:305-313.

38. Tsunoda S, Sakurai H, Saito Y, Ueno Y, Koizumi K, Saiki I: Massive T-lymphocyte infiltration into the host stroma is essential for fibroblast growth factor-2-promoted growth and metastasis of mammary tumors via neovascular stability. Am J Pathol 2009, 174:671-683.

39. Theodorou V, Boer M, Weigelt B, Jonkers J, van der Valk M, Hilkens J: Fgf10 is an oncogene activated by MMTV insertional mutagenesis in mouse mammary tumors and overexpressed in a subset of human breast carcinomas. Oncogene 2004, 23:6047-6055.

40. Sorrell JM, Caplan AI: Fibroblasts: a diverse population at the center of it all. Int Rev Cell Mol Biol 2009, 276:161-214.

41. Norrel RM, Holm MV, Bieche I, Ponder BA, Vihinen M, Bierne N: The role of Biallelic expression polymorphisms in the regulation of fibroblast growth factor 2 gene expression and breast cancer risk. Breast Cancer Res 2009, 11:2267-2282.

42. Rinn JL, Biede C, Gladstone HB, Brown PO, Chang HY: Anatomic demarcation by positional variation in fibroblast gene expression programs. Proc Natl Acad Sci USA 2002, 99:12877-12882.

43. Nolte SV, Xu W, Rennekampff HO, Rodemann HP: Diversity of fibroblasts: a review on implications for skin tissue engineering. Cells Tissues Organs 2008, 187:165-176.

44. Huang GJ, Shifman S, Valdar W, Johannesson M, Yalcin B, Taylor MS, Taylor JM, Mott R, Flint J: High resolution mapping of expression QTLs in heterogeneous stock mice in multiple tissues. Genom Res 2009, 19:1133-1140.

45. Huijts et al: Allele-specific regulation of FGFR2 expression is cell type-dependent and may increase breast cancer risk through a paracrine stimulus involving FGF10. Breast Cancer Research 2011 13:R72.