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DNA Glycosylases Involved in Base Excision Repair May Be Associated with Cancer Risk in *BRCA1* and *BRCA2* Mutation Carriers

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Abstract

Single Nucleotide Polymorphisms (SNPs) in genes involved in the DNA Base Excision Repair (BER) pathway could be associated with cancer risk in carriers of mutations in the high-penetrance susceptibility genes *BRCA1* and *BRCA2*, given the relation of synthetic lethality that exists between one of the components of the BER pathway, PARP1 (poly ADP ribose polymerase), and both *BRCA1* and *BRCA2*. In the present study, we have performed a comprehensive analysis of 18 genes involved in BER using a tagging SNP approach in a large series of *BRCA1* and *BRCA2* mutation carriers. 144 SNPs were analyzed in a two stage study involving 23,463 carriers from the CIMBA consortium (the Consortium of Investigators of Modifiers of *BRCA1* and *BRCA2*). Eleven SNPs showed evidence of association with breast and/or ovarian cancer at $p < 0.05$ in the combined analysis. Four of the five genes for which strongest evidence of association was observed were DNA glycosylases. The strongest evidence was for rs1466785 in the *NEIL2* (endonuclease VIII-like 2) gene (HR: 1.09, 95% CI (1.03–1.16), $p = 2.7 \times 10^{-3}$) for association with breast cancer risk in *BRCA2* mutation carriers, and rs2304277 in the *OGG1* (8-guanine DNA glycosylase) gene, with ovarian cancer risk in *BRCA1* mutation carriers (HR: 1.12 95%CI: 1.03–1.21, $p = 4.8 \times 10^{-3}$). DNA glycosylases involved in the first steps of the BER pathway may be associated with cancer risk in *BRCA1/2* mutation carriers and should be more comprehensively studied.

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Introduction

Carrying an inherited mutation in the *BRCA1* or *BRCA2* gene increases a woman's lifetime risk of developing breast, ovarian and other cancers. The estimated cumulative risk of developing breast cancer by the age of 70 in *BRCA1* and *BRCA2* mutation carriers varies between 43% to 88%; similarly, between 11% to 59% of mutation carriers will develop ovarian cancer by the age of 70 [1–3]. These considerable differences in disease manifestation suggest the existence of other genetic or environmental factors that modify the risk of cancer development. The Consortium of Investigators of Modifiers of *BRCA1* and *BRCA2* (CIMBA), was established in 2006 [4] and with more than 40,000 mutation carriers currently provides the largest sample size for reliable evaluation of even modest associations between single-nucleotide polymorphisms (SNPs) and cancer risk. CIMBA studies have so far demonstrated that more than 25 SNPs are associated with the risk of developing breast or ovarian cancer for *BRCA1* or *BRCA2* carriers. These were identified through genome-wide association studies (GWAS) of breast or ovarian cancer in the general population or through *BRCA1*- and *BRCA2*-specific GWAS [5–8]. Cells harboring mutations in *BRCA1* or *BRCA2* show impaired homologous recombination (HR) [9–11] and are thus critically dependent on other members of the DNA repair machinery such as poly ADP ribose polymerase (PARP1) involved in the Base Excision Repair (BER) pathway. The BER pathway is crucial for the replacement of aberrant bases generated by different causes [12]. A deficiency in BER can give rise to a further accumulation of double-strand DNA breaks which, in the presence of a defective *BRCA1* or *BRCA2* background, could persist and lead to cell cycle arrest or cell death; this makes BRCA-deficient cells extremely sensitive to

PARP inhibitors, as previously demonstrated [13]. We hypothesize that SNPs in *PARP1* and other members of BER may be associated with cancer risk in *BRCA1* and *BRCA2* mutation carriers. SNPs in *XRCC1*, one of the main components of BER, have been recently evaluated within the CIMBA consortium [14], however a comprehensive study has not yet been performed of either *XRCC1* or the other genes participating in BER.

In the present study, we used a tagging SNP approach to evaluate whether the common genetic variation in the genes involved in the BER pathway could be associated with cancer risk in a large series of *BRCA1/2* mutation carriers using a two-stage approach. The first stage involved an analysis of 144 tag SNPs in 1,787 Spanish and Italian *BRCA1/2* mutation carriers. In stage II, the 36 SNPs showing the strongest evidence of association in stage I, were evaluated in a further 23,463 CIMBA mutation carriers included in the Collaborative Oncological Gene-environment Study (COGS) and genotyped using the iCOGS custom genotyping array.

Results

Breast cancer association

In stage I, 144 selected Tag SNPs covering the 18 selected BER genes were genotyped in 968 *BRCA1* and 819 *BRCA2* mutation carriers from five CIMBA centres (Spanish National Cancer Research Centre (CNIO), Hospital Clínico San Carlos (HCSC), Catalan Institute of Oncology (ICO), Demokritos and Milan Breast Cancer Study Group (MBCSG). Of those, 50 were excluded because of low call-rates, minor allele frequency (MAF) < 0.05, evidence of deviation from Hardy Weinberg Equilibrium (p -value < 10^{-3}) or monomorphism. Associations with

Author Summary

Women harboring a germ-line mutation in the *BRCA1* or *BRCA2* genes have a high lifetime risk to develop breast and/or ovarian cancer. However, not all carriers develop cancer and high variability exists regarding age of onset of the disease and type of tumor. One of the causes of this variability lies in other genetic factors that modulate the phenotype, the so-called modifier genes. Identification of these genes might have important implications for risk assessment and decision making regarding prevention of the disease. Given that *BRCA1* and *BRCA2* participate in the repair of DNA double strand breaks, here we have investigated whether variations, Single Nucleotide Polymorphisms (SNPs), in genes participating in other DNA repair pathway may be associated with cancer risk in *BRCA* carriers. We have selected the Base Excision Repair pathway because *BRCA* defective cells are extremely sensitive to the inhibition of one of its components, PARP1. Thanks to a large international collaborative effort, we have been able to identify at least two SNPs that are associated with increased cancer risk in *BRCA1* and *BRCA2* mutation carriers respectively. These findings could have implications not only for risk assessment, but also for treatment of *BRCA1/2* mutation carriers with PARP inhibitors.

breast cancer risk were assessed for 94 SNPs, as summarized in Table S1. The 36 SNPs that showed evidence of association at $p \leq 0.05$ were selected for analysis in stage II. Of the 36 SNPs successfully genotyped in the whole CIMBA series comprising 15,252 *BRCA1* and 8211 *BRCA2* mutation carriers, consistent evidence of association with breast cancer risk ($p\text{-trend} < 0.05$) was observed for six SNPs (Table 1). The strongest evidence of association was observed for rs1466785 in the *NEIL2* gene (HR: 1.09, 95% CI (1.03–1.16), $p = 2.7 \times 10^{-3}$) for association with breast cancer risk in *BRCA2* mutation carriers. We had observed a consistent association in stage I in *BRCA2* mutation carriers (HR: 1.25, $p = 0.06$). The SNP was primarily associated with ER-negative breast cancer (HR: 1.20, 95%CI (1.06–1.37), $p = 4 \times 10^{-3}$), although the difference in HRs for ER-positive and ER-negative disease was not statistically significant. The evidence of association in Stage II was somewhat stronger when considering the genotype-specific models, with the dominant being the best fitting (HR: 1.20 95% CI: 1.09–1.37, $p = 1 \times 10^{-4}$). The associations remained significant and the estimated effect sizes remained consistent with the overall analysis when the data were reanalyzed excluding samples used in stage I of the study (data not shown). Imputation using the 1000 genomes data showed that there were several SNPs in strong linkage disequilibrium (LD) with rs1466785 showing more significant associations ($p < 10^{-3}$) (Figure 1).

Ovarian cancer association

Due to lack of power we did not perform analysis of associations with ovarian cancer in stage I. However, we performed this analysis for the 36 SNPs tested in stage II. Although they had been selected based on their evidence of association with breast cancer risk, under the initial hypothesis they are also plausible modifiers of ovarian cancer risk for *BRCA1* and *BRCA2* mutation carriers. We found four SNPs associated with ovarian cancer risk with a $p\text{-trend} < 0.01$ in *BRCA1* or *BRCA2* mutation carriers (Table 1). The strongest association was found for rs2304277 in *OGG1* in *BRCA1* mutation carriers (HR: 1.12, 95%CI: 1.03–1.21, $p = 4.8 \times 10^{-3}$).

The association was somewhat stronger under the dominant model (HR: 1.19, 95%CI: 1.08–1.3, $p = 6 \times 10^{-4}$). Although three other SNPs were found to be associated with ovarian cancer risk in *BRCA2* mutation carriers ($p\text{-trend} < 10^{-3}$), these results were based on a relatively small number of ovarian cancer cases. Imputed data did not show any SNPs with substantially more significant associations with ovarian cancer risk except for rs3093926 in *PARP2*, associated with ovarian cancer risk in *BRCA2* mutation carriers for which there was a SNP, rs61995542, with a stronger association (HR: 0.67, $p = 4.6 \times 10^{-4}$) (Figure S1).

Discussion

Based on the interaction of synthetic lethality that has been described between *PARP1* and both *BRCA1* and *BRCA2*, we hypothesize that this and other genes involved in the BER pathway could potentially be associated with cancer risk in *BRCA1/2* mutation carriers. Several studies have recently investigated the association of some of the BER genes with breast cancer, however, no definitive conclusions can be drawn, given that some publications suggest that SNPs in these genes can be associated with breast cancer risk with marginal p -values while others rule out a major role of these genes in the disease [15–21]. There is only one study from the CIMBA consortium which has evaluated the role of three of the most studied SNPs in the *XRCC1* gene, c.-77C>T (rs3213245) p.Arg280His (rs25489) and p.Gln399Arg (rs25487), ruling out associations of these variants with cancer risk in *BRCA1* and *BRCA2* mutation carriers [14]. However, a comprehensive analysis of neither *XRCC1* nor the other genes involved in the pathway in the context of *BRCA* mutation carriers has been performed. In the present study we have assessed the common genetic variation of 18 genes participating in BER by using a two stage strategy.

Eleven SNPs showed evidence of association with breast and/or ovarian cancer at $p < 0.05$ in stage II of the experiment (Table 1). Of those, six showed a $p\text{-trend} < 0.01$ and were therefore considered the best candidates for further evaluation. Only one of those six, rs1466785 in the *NEIL2* gene (endonuclease VIII-like 2) showed an association with breast cancer risk while the other five, rs2304277 in *OGG1* (8-guanine DNA glycosylase), rs167715 and rs4135087 in *TDG* (thymine-DNA glycosylase), rs3093926 in *PARP2* (Poly(ADP-ribose) polymerase 2) and rs34259 in *UNG* (uracil-DNA glycosylase) were associated with ovarian cancer risk.

The minor allele of *NEIL2*-rs1466785 was associated with increased breast cancer risk in *BRCA2* mutation carriers; moreover, when considering the genotype-specific risks observed that the best fitting model was the dominant one. *NEIL2* is one of the oxidized base-specific DNA glycosylases that participate in the initial steps of BER and specifically removes oxidized bases from transcribing genes [22]. By imputing using the 1000 genome data we found six correlated SNPs in strong LD with rs1466785 ($r^2 > 0.8$), located closer or inside the gene and showing slightly stronger and more significant associations with the disease and therefore being better candidate causal variants. From those, we considered rs804276 and rs804271 as the best candidates given that they showed the most significant associations ($p = 6 \times 10^{-4}$ and $p = 8 \times 10^{-4}$ respectively) and there were available epidemiological or functional data supporting their putative role in cancer. SNP rs804276 has been associated with disease recurrence in patients with bladder cancer treated with Bacillus Calmette-Guérin (BCG) (HR: 2.71, 95%CI (1.75–4.20), $p = 9 \times 10^{-6}$) [23]. SNP rs804271 is located in a positive regulatory region in the promoter of the gene, between two potential cis-binding sites for reactive oxygen species responsive transcription factors in which sequence variation has

Table 1. Associations with breast and ovarian cancer risk for SNPs observed at $p\text{-trend} < 0.05$ in stage II of the experiment.

<i>BRCA1</i> carriers	SNP name	Gene	Unaffected (Number)	Affected (Number)	Unaffected (MAF)	Affected (MAF)	HR per allele ^a	HR heterozygote ^b	HR homozygote ^b	p-trend ^c	p-het ^c	p-hom ^c
Breast cancer	rs3847954 ^d	UNG	7455	7797	0.18	0.19	1.05 (1.00–1.11)	1.09 (1.02–1.16)	0.99 (0.84–1.16)	0.04	0.011	0.713
Ovarian cancer	rs2072668	OGG1	12786	2461	0.22	0.23	1.09 (1.01–1.18)	1.16 (1.05–1.27)	1.03 (0.82–1.28)	0.016	3×10^{-3}	0.77
	rs2269112	OGG1	12789	2461	0.17	0.18	1.11 (1.02–1.21)	1.11 (1.01–1.23)	1.21 (0.92–1.58)	0.013	0.014	0.268
	rs2304277	<i>OGG1</i>	12783	2462	0.2	0.21	1.12 (1.03–1.21)	1.19 (1.08–1.3)	1.01 (0.79–1.30)	4.8×10^{-3}	6×10^{-4}	0.69
	rs10161263	SMUG1	12790	2462	0.34	0.32	0.92 (0.86–0.99)	0.88 (0.80–0.97)	0.90 (0.78–1.04)	0.024	9×10^{-3}	0.49
<i>BRCA2</i> carriers	SNP name	Gene	Unaffected (Number)	Affected (Number)	Unaffected (MAF)	Affected (MAF)	HR per allele	HR heterozygote	HR homozygote	p-trend	p-het	p-hom
Breast cancer	rs2072668 ^e	OGG1	3879	4328	0.23	0.21	0.91 (0.85–0.98)	0.95 (0.87–1.04)	0.75 (0.62–0.91)	0.018	0.098	7×10^{-3}
	rs2269112 ^f	OGG1	3880	4329	0.17	0.16	0.91 (0.84–0.99)	0.93 (0.85–1.03)	0.76 (0.58–0.99)	0.035	0.083	0.054
	rs3136811 ^g	POLB	3873	4321	0.06	0.07	1.12 (1.005–1.25)	1.17 (1.03–1.32)	0.86 (0.49–1.48)	0.032	0.019	0.715
	rs2304277 ^h	OGG1	3880	4330	0.21	0.19	0.91 (0.84–0.97)	0.94 (0.85–1.03)	0.74 (0.60–0.91)	0.013	0.058	0.01
	rs1466785ⁱ	<i>NEIL2</i>	3879	4330	0.4	0.43	1.09 (1.03–1.16)	1.20 (1.09–1.37)	1.16 (1.03–1.31)	2.7×10^{-3}	1×10^{-4}	0.455
Ovarian cancer	rs167715	<i>TDG</i>	7577	631	0.12	0.09	0.76 (0.62–0.94)	0.72 (0.58–0.90)	0.89 (0.41–1.89)	7.4×10^{-3}	4.1×10^{-3}	0.866
	rs3093926^j	<i>PARP2</i>	7580	631	0.07	0.05	0.64 (0.49–0.84)	–	–	1.5×10^{-3}	–	–
	rs4135087	<i>TDG</i>	7580	631	0.09	0.11	1.32 (1.09–1.59)	1.33 (1.07–1.65)	1.67 (0.84–3.28)	2.8×10^{-3}	3.8×10^{-3}	0.185
	rs34259	<i>UNG</i>	7580	631	0.2	0.17	0.80 (0.69–0.94)	0.84 (0.70–1.01)	0.51 (0.29–0.90)	7.6×10^{-3}	0.025	0.028

^aHazard Ratio per allele (1 df) estimated from the retrospective likelihood analysis.^bHazard Ratio under the genotype specific models (2df) estimated from the retrospective likelihood analysis.^cp-values were based on the score test.^dHR per allele of 1.69 and p-trend of 1×10^{-4} for *BRCA2* mutation carriers in stage I of the study.^eHR per allele of 1.43 and p-trend of 0.01 for *BRCA1* mutation carriers in stage I of the study.^fHR per allele of 1.30 and p-trend of 0.03 for *BRCA1* mutation carriers in stage I of the study.^gHR per allele of 0.64 and p-trend of 0.057 for *BRCA2* mutation carriers in stage I of the study.^hHR per allele of 1.25 and p-trend of 0.04 for *BRCA1* mutation carriers in stage I of the study.ⁱHR per allele of 1.25 and p-trend of 0.058 for *BRCA2* mutation carriers in stage I of the study.^jrs3093926 did not yield results under the genotype specific model due to the low minor allele frequency.

Complete description of results from stage I are included in Supplementary Table S1.

Highlighted in bold are those SNPs showing strongest associations with breast or ovarian cancer risk ($p < 0.01$).

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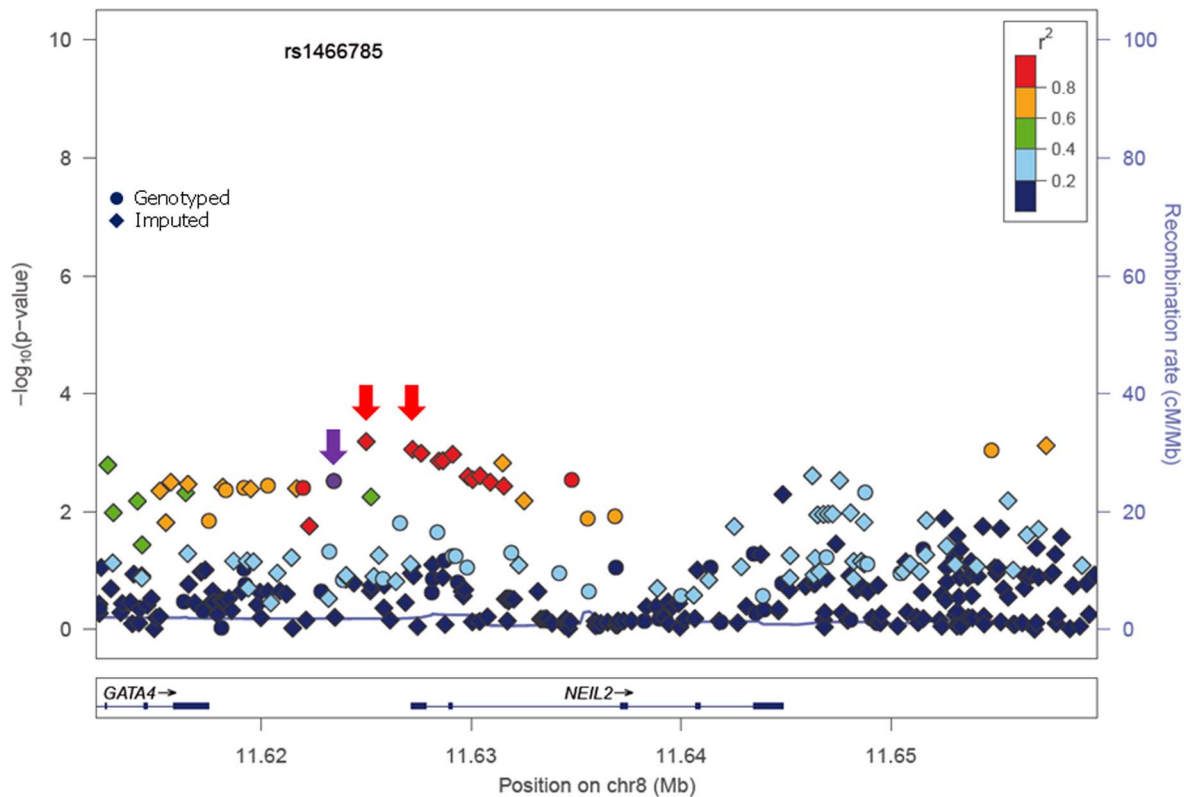


Figure 1. p-values of association ($-\log_{10}$ scale) with breast cancer risk in *BRCA2* carriers for genotyped and imputed SNPs in the *NEIL2* gene. SNP rs1466785 is indicated with a purple arrow and the best causal imputed SNPs, rs804276 and rs804271 are indicated with a red arrow. Colors represent the pairwise r^2 . Plot generated with LocusZoom [42] (<http://csg.sph.umich.edu/locuszoom/>). doi:10.1371/journal.pgen.1004256.g001

been proven to alter the transcriptional response to oxidative stress [24]. Moreover, this SNP has been proposed to partly explain the inter-individual variability observed in *NEIL2* expression levels in the general population and has been proposed as a potential risk modifier of disease susceptibility [25].

Several studies have been published showing associations between SNPs in *NEIL2* and lung or oropharyngeal cancer risk [26,27] but to our knowledge, no association with breast cancer risk has been reported. We hypothesize that the potential association observed in the present study could be explained by the interaction between *NEIL2* and *BRCA2*, each of them causing a deficiency in the BER and HR DNA repair pathways, respectively. This would explain why the breast cancer risk modification due to rs1466785 would only be detected in the context of *BRCA2* mutation carriers and not in the general population.

The strongest evidence of association found in *BRCA1* carriers was between rs2304277 in the *OGG1* gene and ovarian cancer risk. The association was more significant when considering the dominant model. *OGG1* removes 8-oxodeoxyguanosine which is generated by oxidative stress and is highly mutagenic, and it has been suggested that SNPs in the gene could be associated with cancer risk [28–31]. This is an interesting result, given that to date only one SNP, rs4691139 in the 4q35.3 region, also identified through the iCOGS effort, has been found to modify ovarian cancer risk specifically in *BRCA1* carriers [32]. SNP rs2304277 is located in the 3'UTR (untranslated region) of the gene and is probably not the causal variant, however, in this case imputations

through the 1000 Genome did not show better results for a more plausible causal SNP.

We have identified four SNPs associated with ovarian cancer risk in *BRCA2* mutation carriers, rs167715 and rs4135087 in the *TDG* gene, rs34259 in the *UNG* gene and rs3093926 in *PARP2*. However, these last results should be interpreted with caution given that the number of *BRCA2* carriers affected with ovarian cancer is four-fold lower than for *BRCA1* carriers and the statistical power was therefore more limited, increasing the possibility of false-positives. In the case of *PARP2*, imputed data showed a lower p-value of association (4×10^{-4}) for another SNP, rs61995542, that had a slightly higher MAF than rs3093926 (0.074 vs. 0.067) (Figure S1). However, it must still be interpreted with caution due to small number of ovarian cancer cases in the *BRCA2* group.

It is worth noting that, four of the five genes for which strongest evidence of association was observed, are all DNA glycosylases participating in the initiation of BER by removing damaged or mismatched bases. Apart from the already mentioned *NEIL2* and *OGG1*, *TDG* initiates repair of G/T and G/U mismatches commonly associated with CpG islands, while *UNG* removes uracil in DNA resulting from deamination of cytosine or replicative incorporation of dUMP. We have not found strong associations with SNPs in genes involved in any other parts of the pathway, such as strand incision, trimming of ends, gap filling or ligation. It has been suggested that at least in the case of uracil repair, base removal is the major rate-limiting step of BER [33]. This is consistent with our findings, suggesting that SNPs causing impairment in the function of these specific DNA glycosylases

non-independence among related individuals, we accounted for the correlation between the genotypes by estimating the kinship coefficient for each pair of individuals using the available genomic data [34,38,39]. These analyses were performed in R using the GenABEL libraries and custom-written functions in FORTRAN and Python.

To estimate the magnitude of the associations (HRs), the effect of each SNP was modeled either as a per-allele HR (multiplicative model) or as genotype-specific HRs, and was estimated on the log-scale by maximizing the retrospective likelihood. The retrospective likelihood was fitted using the pedigree-analysis software MENDEL. The variances of the parameter estimates were obtained by robust variance estimation based on reported family membership. All analyses were stratified by country of residence and based on calendar-year and cohort-specific breast cancer incidence rates for mutation carriers. Countries with small number of mutation carriers were combined with neighbouring countries to ensure sufficiently large numbers within each stratum. USA and Canada were further stratified by reported Ashkenazi Jewish (AJ) ancestry.

Imputation. Genotypes were imputed separately for *BRCA1* and *BRCA2* mutation carriers using the v3 April 2012 release (Genomes Project et al., 2012) as reference panel. To improve computation efficiency we used a two-step procedure which involved pre-phasing in the first step and imputation of the phased data in the second. Pre-phasing was carried out using the SHAPEIT software [40]. The IMPUTE version 2 software was used for the subsequent imputation [41]. SNPs were excluded from the association analysis if their imputation accuracy was $r^2 < 0.3$ or $MAF < 0.005$ in any of the data sets. For the final analysis we only took in account those SNPs with an imputation accuracy $r^2 > 0.7$, $MAF > 0.01$ and being located in the region comprised within 15 kilo bases (kb) downstream and upstream the gene where the genotyped SNP showing an association was located (Table 1). Associations between imputed genotypes and breast cancer risk were evaluated using a version of the score test as described above but with the posterior genotype probabilities replacing the genotypes.

Supporting Information

Figure S1 p-values of association ($-\log_{10}$ scale) with breast and ovarian cancer risk in *BRCA1* and *BRCA2* carriers for genotyped and imputed SNPs considering 15 kb upstream and downstream the genes in which SNPs described in Table 1 were located. rs numbers of SNPs from Table 1 are indicated at the top of each panel and in the graph with a purple arrow. For *PARP2* gene, the imputed SNP with the strongest association, rs61995542 is indicated with a red arrow. Colors represent the pairwise r^2 . (PPT)

Table S1 Association with breast cancer for the 94 SNPs selected for analysis in stage I. (XLS)

Table S2 number of *BRCA1* and *BRCA2* carriers by study. (XLS)

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References

- Antoniou A, Pharoah PD, Narod S, Risch HA, Eyfjord JE, et al. (2003) Average risks of breast and ovarian cancer associated with *BRCA1* or *BRCA2* mutations detected in case Series unselected for family history: a combined analysis of 22 studies. *Am J Hum Genet* 72: 1117–1130.
- Chen S, Iversen ES, Friebe T, Finkelstein D, Weber BL, et al. (2006) Characterization of *BRCA1* and *BRCA2* mutations in a large United States sample. *J Clin Oncol* 24: 863–871.
- Milne RL, Osorio A, Cajas TR, Vega A, Lloret G, et al. (2008) The average cumulative risks of breast and ovarian cancer for carriers of mutations in *BRCA1* and *BRCA2* attending genetic counseling units in Spain. *Clin Cancer Res* 14: 2861–2869.
- Chenevix-Trench G, Milne RL, Antoniou AC, Couch FJ, Easton DF, et al. (2007) An international initiative to identify genetic modifiers of cancer risk in *BRCA1* and *BRCA2* mutation carriers: the Consortium of Investigators of Modifiers of *BRCA1* and *BRCA2* (CIMBA). *Breast Cancer Res* 9: 104.
- Antoniou AC, Kuchenbaecker KB, Soucy P, Beesley J, Chen X, et al. (2012) Common variants at 12p11, 12q24, 9p21, 9q31.2 and in *ZNF365* are associated with breast cancer risk for *BRCA1* and/or *BRCA2* mutation carriers. *Breast Cancer Res* 14: R33.
- Antoniou AC, Spurdle AB, Sinilnikova OM, Healey S, Pooley KA, et al. (2008) Common breast cancer-predisposition alleles are associated with breast cancer risk in *BRCA1* and *BRCA2* mutation carriers. *Am J Hum Genet* 82: 937–948.
- Antoniou AC, Sinilnikova OM, McGuffog L, Healey S, Nevanlinna H, et al. (2009) Common variants in *LSP1*, 2q35 and 8q24 and breast cancer risk for *BRCA1* and *BRCA2* mutation carriers. *Hum Mol Genet* 18: 4442–4456.
- Antoniou AC, Wang X, Fredericksen ZS, McGuffog L, Tarrell R, et al. (2010) A locus on 19p13 modifies risk of breast cancer in *BRCA1* mutation carriers and is associated with hormone receptor-negative breast cancer in the general population. *Nat Genet* 42: 885–892.
- Antoniou AC, Sinilnikova OM, Simard J, Leone M, Dumont M, et al. (2007) *RAD51* 135G→C modifies breast cancer risk among *BRCA2* mutation carriers: results from a combined analysis of 19 studies. *Am J Hum Genet* 81: 1186–1200.
- Moynahan ME, Chiu JW, Koller BH, Jasin M (1999) *Brc1* controls homology-directed DNA repair. *Mol Cell* 4: 511–518.
- Patel KJ, Yu VP, Lee H, Corcoran A, Thistlethwaite FC, et al. (1998) Involvement of *Brc2* in DNA repair. *Mol Cell* 1: 347–357.
- Xu G, Herzog M, Rotrekl V, Walter CA (2008) Base excision repair, aging and health span. *Mech Ageing Dev* 129: 366–382.
- Farmer H, McCabe N, Lord CJ, Tutt AN, Johnson DA, et al. (2005) Targeting the DNA repair defect in *BRCA* mutant cells as a therapeutic strategy. *Nature* 434: 917–921.
- Osorio A, Milne RL, Alonso R, Pita G, Peterlongo P, et al. (2011) Evaluation of the *XRCC1* gene as a phenotypic modifier in *BRCA1/2* mutation carriers. Results from the consortium of investigators of modifiers of *BRCA1/BRCA2*. *Br J Cancer* 104: 1356–1361.
- Zhang Y, Newcomb PA, Egan KM, Titus-Ernstoff L, Chanock S, et al. (2006) Genetic polymorphisms in base-excision repair pathway genes and risk of breast cancer. *Cancer Epidemiol Biomarkers Prev* 15: 353–358.
- Zipprich A, Kuss O, Rogowski S, Kleber G, Lotterer E, et al. (2010) Incorporating indocyanin green clearance into the Model for End Stage Liver Disease (MELD-ICG) improves prognostic accuracy in intermediate to advanced cirrhosis. *Gut* 59: 963–968.
- Popanda O, Seibold P, Nikolov I, Oakes CC, Burwinkel B, et al. (2013) Germline variants of base excision repair genes and breast cancer: A polymorphism in DNA polymerase gamma modifies gene expression and breast cancer risk. *Int J Cancer* 132: 55–62.
- Roberts MR, Shields PG, Ambrosone CB, Nie J, Marian C, et al. (2011) Single-nucleotide polymorphisms in DNA repair genes and association with breast cancer risk in the web study. *Carcinogenesis* 32: 1223–1230.
- Sangrajrang S, Schmezer P, Burkholder I, Waas P, Boffetta P, et al. (2008) Polymorphisms in three base excision repair genes and breast cancer risk in Thai women. *Breast Cancer Res Treat* 111: 279–288.
- Ming-Shian H, Yu JC, Wang HW, Chen ST, Hsiung CN, et al. (2010) Synergistic effects of polymorphisms in DNA repair genes and endogenous estrogen exposure on female breast cancer risk. *Ann Surg Oncol* 17: 760–771.
- Zipprich J, Terry MB, Brandt-Rauf P, Freyer GA, Liao Y, et al. (2010) *XRCC1* polymorphisms and breast cancer risk from the New York Site of the Breast Cancer Family Registry: A family-based case-control study. *J Carcinog* 9: 4.
- Banerjee D, Mandal SM, Das A, Hegde ML, Das S, et al. (2011) Preferential repair of oxidized base damage in the transcribed genes of mammalian cells. *J Biol Chem* 286: 6006–6016.
- Wei H, Kamat A, Chen M, Ke HL, Chang DW, et al. (2012) Association of polymorphisms in oxidative stress genes with clinical outcomes for bladder cancer treated with *Bacillus Calmette-Guerin*. *PLoS One* 7: e38533.
- Kinslow CJ, El-Zein RA, Rondelli CM, Hill CE, Wickliffe JK, et al. (2010) Regulatory regions responsive to oxidative stress in the promoter of the human DNA glycosylase gene *NEIL2*. *Mutagenesis* 25: 171–177.
- Kinslow CJ, El-Zein RA, Hill CE, Wickliffe JK, Abdel-Rahman SZ (2008) Single nucleotide polymorphisms 5' upstream the coding region of the *NEIL2* gene influence gene transcription levels and alter levels of genetic damage. *Genes Chromosomes Cancer* 47: 923–932.
- Dey S, Maiti AK, Hegde ML, Hegde PM, Boldogh I, et al. (2012) Increased risk of lung cancer associated with a functionally impaired polymorphic variant of the human DNA glycosylase *NEIL2*. *DNA Repair (Amst)* 11: 570–578.
- Zhai X, Zhao H, Liu Z, Wang LE, El-Naggar AK, et al. (2008) Functional variants of the *NEIL1* and *NEIL2* genes and risk and progression of squamous cell carcinoma of the oral cavity and oropharynx. *Clin Cancer Res* 14: 4345–4352.
- Arcand SL, Provencher D, Mes-Masson AM, Tonin PN (2005) *OGG1* Cys326 variant, allelic imbalance of chromosome band 3p25.3 and TP53 mutations in ovarian cancer. *Int J Oncol* 27: 1315–1320.
- Rosner P, Jr., Terry MB, Gammon MD, Zhang FF, Teitelbaum SL, et al. (2006) *OGG1* polymorphisms and breast cancer risk. *Cancer Epidemiol Biomarkers Prev* 15: 811–815.
- Wei W, He XF, Qin JB, Su J, Li SX, et al. (2012) Association between the *OGG1* Ser326Cys and *APEX1* Asp148Glu polymorphisms and lung cancer risk: a meta-analysis. *Mol Biol Rep* 39: 11249–11262.
- Xie Y, Yang H, Miller JH, Shih DM, Hicks GG, et al. (2008) Cells deficient in oxidative DNA damage repair genes *Myh* and *Ogg1* are sensitive to oxidants with increased G2/M arrest and multinucleation. *Carcinogenesis* 29: 722–728.
- Couch FJ, Wang X, McGuffog L, Lee A, Olswood C, et al. (2013) Genome-Wide Association Study in *BRCA1* Mutation Carriers Identifies Novel Loci Associated with Breast and Ovarian Cancer Risk. *PLoS Genet* 9: e1003212.
- Visnes T, Akbari M, Hagen L, Slupphaug G, Krokan HE (2008) The rate of base excision repair of uracil is controlled by the initiating glycosylase. *DNA Repair (Amst)* 7: 1869–1881.
- Antoniou AC, Goldgar DE, Andrieu N, Chang-Claude J, Brohet R, et al. (2005) A weighted cohort approach for analysing factors modifying disease risks in carriers of high-risk susceptibility genes. *Genet Epidemiol* 29: 1–11.
- Gaudet MM, Kuchenbaecker KB, Vijai J, Klein RJ, Kirchhoff T, et al. (2013) Identification of a *BRCA2*-Specific Modifier Locus at 6p24 Related to Breast Cancer Risk. *PLoS Genet* 9: e1003173.
- Barnes DR, Lee A, Easton DF, Antoniou AC (2012) Evaluation of association methods for analysing modifiers of disease risk in carriers of high-risk mutations. *Genet Epidemiol* 36: 274–291.

37. Barnes DR, Antoniou AC (2012) Unravelling modifiers of breast and ovarian cancer risk for *BRCA1* and *BRCA2* mutation carriers: update on genetic modifiers. *J Intern Med* 271: 331–343.
38. Amin N, van Duijn CM, Aulchenko YS (2007) A genomic background based method for association analysis in related individuals. *PLoS One* 2: e1274.
39. Leutenegger AL, Prum B, Genin E, Verny C, Lemaître A, et al. (2003) Estimation of the inbreeding coefficient through use of genomic data. *Am J Hum Genet* 73: 516–523.
40. Delaneau O, Zagury JF (2012) Haplotype inference. *Methods Mol Biol* 888: 177–196.
41. Howie BN, Donnelly P, Marchini J (2009) A flexible and accurate genotype imputation method for the next generation of genome-wide association studies. *PLoS Genet* 5: e1000529.
42. Pruim RJ, Welch RP, Sanna S, Teslovich TM, Chines PS, et al. (2010) LocusZoom: regional visualization of genome-wide association scan results. *Bioinformatics* 26: 2336–2337.