

Breast Cancer Polygenic Risk Score and Contralateral Breast Cancer Risk

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Summary

Previous research has shown that polygenic risk scores (PRSs) can be used to stratify women according to their risk of developing primary invasive breast cancer. This study aimed to evaluate the association between a recently validated PRS of 313 germline variants (PRS₃₁₃) and contralateral breast cancer (CBC) risk. We included 56,068 women of European ancestry diagnosed with first invasive breast cancer from 1990 onward with follow-up from the Breast Cancer Association Consortium. Metachronous CBC risk (N = 1,027) according to the distribution of PRS₃₁₃ was quantified using Cox regression analyses. We assessed PRS₃₁₃ interaction with age at first diagnosis, family history, morphology, ER status, PR status, and HER2 status, and (neo)adjuvant therapy. In studies of Asian women, with limited follow-up, CBC risk associated with PRS₃₁₃ was assessed using logistic regression for 340 women with CBC compared with 12,133 women with unilateral breast cancer. Higher PRS₃₁₃ was associated with increased CBC risk: hazard ratio per standard deviation (SD) = 1.25 (95%CI = 1.18–1.33) for Europeans, and an OR per SD = 1.15 (95%CI = 1.02–1.29) for Asians. The absolute lifetime risks of CBC, accounting for death as competing risk, were 12.4% for European women at the 10th percentile and 20.5% at the 90th percentile of PRS₃₁₃. We found no evidence of confounding by or interaction with individual characteristics, characteristics of the primary tumor, or treatment. The C-index for the PRS₃₁₃ alone was 0.563 (95%CI = 0.547–0.586). In conclusion, PRS₃₁₃ is an independent factor associated with CBC risk and can be incorporated into CBC risk prediction models to help improve stratification and optimize surveillance and treatment strategies.

Introduction

Due to the high incidence of breast cancer and improving survival, an increasing number of breast cancer survivors are at risk of developing contralateral breast cancer

(CBC). The 10-year cumulative incidence of CBC is ~4%,^{1,2} but estimates vary widely depending on factors such as germline genetics, family history, and (neo)adjuvant systemic therapy for the first breast cancer.³ The risk of developing CBC is particularly high in women with

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rare mutations in certain genes including *BRCA1*, *BRCA2*, and *CHEK2*, with approximately 2- to 4-fold higher risks reported compared with women without these mutations.³

Recently, genome-wide association studies (GWASs) have identified multiple common germline variants that

are associated with first primary breast cancer risk.^{4,5} These are associated with small differences in risk individually, but their combined effects can be summarized in a polygenic risk score (PRS), which has been shown to stratify women according to their risk of developing breast cancer.^{6–9} Using a large GWAS dataset from the Breast Cancer

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Association Consortium (BCAC), we previously developed and validated a 313-variant PRS (PRS₃₁₃) among women of European descent. In independent prospective studies, this PRS₃₁₃ predicted the risk of primary invasive breast cancer with an odds ratio (OR) per standard deviation (SD) of 1.61 (95% confidence interval (95%CI) = 1.57–1.65).⁷ The PRS₃₁₃ has also been externally validated using the UK Biobank cohort.

The aim of the current study was to evaluate the association between PRS₃₁₃ and CBC risk, using data from BCAC. Other studies have shown associations between risk of CBC and both a 67-variant PRS¹⁰ and individual variants,¹¹ but not yet with PRS₃₁₃, the most extensively validated PRS. Further, the dataset currently evaluated is larger than those previously tested. We carried out two types of analyses. We conducted a cohort study among studies of European ancestry women with follow-up data available and performed Cox regression analyses to estimate hazard ratios (HRs) for CBC. Potential confounding and interaction with characteristics of the individual, characteristics of the primary tumor, or treatment were tested. In addition, to directly compare with the OR reported for PRS₃₁₃ and first breast cancer, we selected case-case series and performed logistic regression analyses comparing the PRS₃₁₃ distribution in women with CBC versus those with unilateral breast cancer. These analyses were conducted separately in European and Asian women (follow-up was too limited to perform a cohort study for the Asian population). Use of PRS₃₁₃ may lead to more accurate CBC risk prediction to support decision making for women who may or may not benefit from additional surveillance and risk-reducing treatment strategies.

Material and Methods

Study Subjects

Case-Case Series

We selected women who were diagnosed with breast cancer and women without any diagnosis of breast cancer from the BCAC including all women of European ancestry, based on genotyping data, and selecting only those studies which reported on CBC (62 studies) (Figure S1A, Table S1 and S2). BCAC database version freeze 12 was used. All women diagnosed with invasive breast cancer as a first cancer were included in the analysis; the small number of tumors with unknown invasiveness were considered invasive (Table S2). In the case-case series, a CBC was defined as a breast cancer (*in situ* or invasive) in the contralateral breast irrespective of the time since the first breast cancer. The case-case series comprised 81,000 women with unilateral breast cancer, 3,607 women with CBC, and 62,830 women without any diagnosis of breast cancer (Figure S1A). We also compared women with unilateral breast cancer to women without any diagnosis of breast cancer to reproduce the estimate that was previously reported for first breast cancer risk⁷ in our study selection.

We selected for a separate analysis women of Asian ancestry from the BCAC data, comprising 12,133 women with unilateral breast cancer, 340 women with CBC, and 13,398 women without

any diagnosis of breast cancer from eight studies (Figure S1B, Table S2).

European Cohort

In the European cohort, we used metachronous CBC as the outcome, defined as a breast cancer in the contralateral breast (*in situ* or invasive) diagnosed at least 3 months after the first breast cancer. We used a cut-off of 3 months to reduce the likelihood that these CBCs represent metastases rather than true second primary tumors. We selected all women diagnosed with breast cancer from the European case-case series and excluded four studies that did not provide follow-up information on vital status (Figure S1A). We did not include Asian women since follow-up was too limited in these studies. We additionally excluded 6,207 women with no follow-up and 2,208 women who developed synchronous CBC, distant metastasis, or who died or were last known to be alive within 3 months after the first breast cancer diagnosis. Since BCAC also included prevalent cases, we excluded 3,796 women who developed CBC or were censored before study entry. The case-case series included women diagnosed between 1947 and 2018. In the European cohort, we excluded 2,235 women who were diagnosed with their first breast cancer before 1990 or who had missing year of first diagnosis. We restricted to women diagnosed from 1990 onward so that diagnostic procedures and treatment would be more representative of current practice. Moreover, clinico-pathological, treatment, and follow-up data were more complete after 1990. In addition, we excluded 16 studies (9,783 women) without information about metachronous CBC events (Figure S1A). After these exclusions, the cohort for this analysis comprised data from 42 studies, including 56,068 women with invasive breast cancer among whom 1,027 metachronous CBC occurred (Table S2).

All individuals provided written informed consent, and all studies were approved by the relevant institutional review boards. BCAC data were centrally harmonized and cleaned in communication with the study data managers and principal investigators. Data collection for individual studies is described in Table S1.

Genotyping and PRSs

DNA samples from participants were genotyped using the iCOGS array^{12,13} or the OncoArray,^{4,14} with genotypes for variants not on the arrays estimated by imputation.^{4,13} The PRS₃₁₃ was calculated as a weighted sum of the minor allele dosages; the variant selection and weights are as given by Mavaddat et al.⁷ We also calculated estimates for a previously published PRS₇₇⁶ and for estrogen receptor (ER)-specific PRSs (ER-positive PRS₃₁₃ and ER-negative PRS₃₁₃).⁷ The ER-specific PRSs were constructed by defining subtype-specific weights for the 313 variants using a hybrid approach.⁷ Variants and corresponding coefficients used to construct the PRS are shown in Table S3. We standardized the PRS in our analyses by dividing it by the SD of the PRS of the control subjects (PRS₇₇ SD = 0.45; PRS₃₁₃ SD = 0.61; ER-positive PRS₃₁₃ SD = 0.65; ER-negative PRS₃₁₃ SD = 0.59) exactly as was done in the analyses of the PRS and first breast cancer risk.^{6,7} This allows a direct comparison of the magnitude of the CBC relative risk estimation to that of the first breast cancer.

For samples genotyped with both OncoArray and iCOGS array (9,071 samples), OncoArray data were used in preference as the imputation quality was generally higher. The intraclass correlation coefficient (ICC) between the PRSs derived from the two platforms was 0.99 (95%CI = 0.99–0.99) for the PRS₇₇ and 0.96 (95%CI = 0.95–0.96) for PRS₃₁₃ (Figure S2). Given the high correlation

between the two platforms, PRS measures from both platforms were used in the analyses without adjustment.

Statistical Analysis

European Cohort

The primary outcome in the European cohort was the development of metachronous CBC. Cox proportional hazards models were used to estimate HRs for metachronous CBC risk by PRS, stratified by country. Since previous studies have shown that age at first breast cancer diagnosis is an important predictor of CBC,³ the analyses were performed with attained age as the timescale. Time at risk started 3 months after the first breast cancer diagnosis and ended at the age of CBC diagnosis, distant metastasis (where available), death, or end of follow-up, whichever came first. For women who had a study entry more than 3 months after first breast cancer diagnosis, follow-up started at the age of study entry. We also performed a fixed-effect meta-analysis of country-specific effects using the STATA command *metan*. We performed a fixed-effect meta-analysis over a random-effect meta-analysis since there was no evidence for heterogeneity in effect sizes between countries (I-squared = 0%, Figure S3). For some analyses, only invasive CBC was used as the outcome; in these analyses we censored on *in situ* CBC. Separate analyses were conducted for ER-positive CBC (censored on ER-negative and ER-unknown CBC) and ER-negative CBC (censored on ER-positive and ER-unknown CBC).

We evaluated the linearity of the association between PRS₃₁₃ per unit SD and CBC risk using restricted cubic splines with three knots. There was no evidence for violation of the linearity assumption. Therefore, in the main analysis, the PRS₃₁₃ was treated as a continuous covariate, and estimated the HR per unit SD of the PRS₃₁₃. Violation of the proportional hazard assumption was assessed by inspection of the Schoenfeld residuals.¹⁵ As a second analysis, we used the per SD log HR of the PRS₃₁₃ to calculate the predicted HR at different percentiles of the PRS₃₁₃, compared to the 50th percentile. Third, the PRS₃₁₃ was categorized into percentile groups (0th to 10th, 10th to 20th, 20th to 40th, 40th to 60th, 60th to 80th, 80th to 90th, 90th to 100th) to illustrate the differences between PRS₃₁₃ subgroups, with the middle quintile (40th to 60th) as the reference.

We also performed multivariable Cox regression analyses to determine whether the log HR of CBC risk by PRS changed when adjusting for year of first breast cancer diagnosis, family history of breast cancer in a first degree relative, and several clinical characteristics of the first breast cancer such as nodal status, tumor size, morphology, ER status, progesterone receptor (PR) status, human epidermal growth factor receptor 2 (HER2) status, (neo) adjuvant chemotherapy, adjuvant endocrine therapy, and radiotherapy. These analyses were performed in all women, a complete case set (excluding those with unknown values for the covariates), and in a set excluding studies oversampling case subjects with family history. Potential effect modification of the PRS₃₁₃ effect by the same variables was evaluated by fitting interaction terms in different models using complete case sets, including the standardized PRS₃₁₃, modifier, and interaction.

The discriminative ability of different models (model 1: PRS₃₁₃ alone; model 2: other risk factors [the adjustment variables from the multivariable Cox regression analyses]; model 3: PRS₃₁₃ + other risk factors) was calculated using Harrell's C-index.¹⁶ Since no standard performance measures are currently available to account for left-truncated follow-up time (i.e., to start analyses at

age at study entry), we used time since first breast cancer as the timescale to calculate the C-index.

Absolute Risks

Absolute risks of developing CBC at PRS₃₁₃ percentiles were calculated using the estimated log HRs per SD from the breast cancer cohort (BCAC) under the log-linear model, assuming the PRS is normally distributed. The PRS₃₁₃ and age-specific incidences were constrained to the age-specific CBC incidences from women diagnosed with a first invasive breast cancer in the period 2003–2010 from the Netherlands Cancer Registry (NCR).¹ The procedure for constraining the incidences has been previously described.¹⁷ The age-specific CBC incidences were calculated overall and for age-specific groups, censoring on death and distant metastasis. We used data from the NCR since this registry has complete coverage of all newly diagnosed cancers in the Netherlands. The NCR cohort included all females aged ≥ 18 years and follow-up for second cancers was complete until February 1, 2016.¹ We then applied the competing risk of dying on the absolute CBC risks. The absolute CBC risk (AR_g) by age t in PRS₃₁₃ category g , taking into account the competing risk of dying was calculated by:

$$AR_g(t) = \sum_{u=0}^{t-1} \mu_g(u) S_g(u) S_m(u)$$

where $\mu_g(t)$ is the CBC incidence associated with PRS₃₁₃ category g , $S_g(t)$ the probability of being free of CBC to age t , and $S_m(t)$ the probability of surviving to age t .

Case-Case Series

For the case-case series (European and Asian), logistic regression models were used to estimate the ORs for CBC risk (comparing with unilateral breast cancer) and for unilateral breast cancer risk (comparing with women without any diagnosis of breast cancer) associated with PRS₃₁₃. All analyses were adjusted for age and country (Table S1). For all unilateral- and contralateral breast cancer patients, we used age at first breast cancer diagnosis, and for women without any diagnosis of breast cancer we used age at baseline questionnaire.

For direct comparison with the estimate reported for PRS₃₁₃ and first breast cancer, we also performed logistic regression analyses in the same BCAC study participants included in the validation of the association between PRS₃₁₃ and first breast cancer.⁷ This validation set comprised a subsample from 24 studies and included 3,781 women with unilateral breast cancer, 94 women with CBC, and 3,753 women without any diagnosis of breast cancer (Table S2). For this analysis, we adjusted for 10 principal components, in line with Mavaddat et al.⁷

For European women who had follow-up time available more than 3 months after the first breast cancer diagnosis, a sensitivity analysis was performed for metachronous CBC (1,702 CBCs). We also did a separate analysis for invasive CBC (N = 3,246), by excluding CBC *in situ*.

All p values are two sided; tests with $p < .05$ are referred to as statistically significant. Analyses were performed using STATA, v.13.1 (StataCorp) and R v.3.3.2.

Results

European (Cohort) Cox Regression Analyses

The European cohort included 56,068 women diagnosed with first invasive breast cancer with 1,027 metachronous CBC events. Median follow-up was 8.4 years. Patient, tumor, and treatment characteristics are summarized in Table S4.

Table 1. Association between PRSs and Contralateral Breast Cancer Risk in the European Cohort (N = 56,068)

Polygenic Risk Score (PRS)	No. of CBC	HR per Unit SD ^a	95%CI	p Value
PRS₇₇^b				
All CBC	1,027	1.21	1.14–1.29	<.001
Invasive CBC	923	1.21	1.13–1.29	<.001
PRS₃₁₃^b				
All CBC	1,027	1.25	1.18–1.33	<.001
Invasive CBC	923	1.24	1.16–1.32	<.001
ER-positive invasive CBC ^d	275	1.38	1.23–1.55	<.001
ER-negative invasive CBC ^d	97	0.92	0.75–1.12	.39
ER-Positive PRS₃₁₃^{b,c}				
All CBC	1,027	1.23	1.16–1.31	<.001
Invasive CBC	923	1.22	1.15–1.30	<.001
ER-positive invasive CBC ^d	275	1.37	1.22–1.54	<.001
ER-Negative PRS₃₁₃^{b,c}				
All CBC	1,027	1.25	1.17–1.33	<.001
Invasive CBC	923	1.24	1.16–1.33	<.001
ER-negative invasive CBC ^d	97	1.06	0.86–1.30	.58

Abbreviations: PRS, polygenic risk score; No., number; CBC, contralateral breast cancer; HR, hazard ratio; CI, confidence interval; ER, estrogen receptor; SD, standard deviation.

^aAll analyses were performed with attained age as timescale.

^bCoefficients to construct the PRSs are shown in Table S3. All PRSs were standardized by the same SD as was used by Mavaddat et al.⁷ The SD was 0.45 for overall breast cancer PRS₇₇, 0.61 for overall breast cancer PRS₃₁₃, 0.65 for ER-positive PRS₃₁₃, and 0.59 for ER-negative PRS₃₁₃.

^cER-specific PRSs were constructed using a hybrid method, as described by Mavaddat et al.⁷

^dWomen with ER-unknown CBC (N = 551) were censored in these analyses.

The associations between the different PRSs and CBC risk are shown in Table 1. The HR for CBC per SD of PRS₃₁₃ was 1.25 (95%CI = 1.18–1.33). For comparison, the HR per SD for PRS₇₇ was 1.21 (95%CI = 1.14–1.29). Women within the 0th to 10th and the 90th to 100th percentile of the PRS₃₁₃ had 0.59-fold (95%CI = 0.45–0.78) and 1.38-fold (95%CI = 1.13–1.69) risk of CBC, respectively, compared with women within the 40th to 60th percentile (Figure 1, Table S5). The predicted HRs of CBC for women at the 10th and 90th percentile of the PRS₃₁₃ were 0.75 and 1.33, respectively, compared to the 50th percentile (Figure 1). Since we observed evidence of departure from the proportional hazards assumption ($p = 0.02$),¹⁵ we also calculated HRs stratified for follow-up duration (<5 and ≥5 years). The HR by SD of the PRS₃₁₃ was 1.21 (95%CI = 1.10–1.32) for CBC diagnosed ≤5 years after first breast cancer diagnosis (CBC N = 428) and 1.28 (95%CI = 1.18–1.38) for CBC diagnosed >5 years after first diagnosis (CBC N = 599).

The HR per SD of PRS₃₁₃ for ER-positive invasive CBC was 1.38 (95%CI = 1.23–1.55) compared to a HR per SD

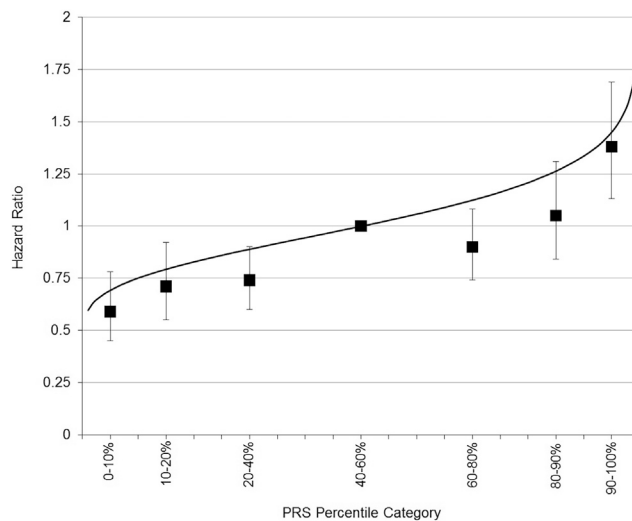


Figure 1. Estimates for Contralateral Breast Cancer Risk by Percentile Categories of the 313-Variant PRS (PRS₃₁₃)

The figure shows the hazard ratios per SD and 95% confidence intervals for percentiles of the PRS₃₁₃ relative to the middle quintile (underlying table can be found in Table S5). The solid line denotes the estimates for contralateral breast cancer risk with the PRS₃₁₃ fitted as a continuous covariate. Coefficients to construct the PRS₃₁₃ are shown in Table S3. The PRS₃₁₃ was standardized by SD = 0.61, in line with Mavaddat et al.⁷ The analyses were performed with attained age as timescale. PRS, polygenic risk score; SD, standard deviation.

of the ER-positive PRS₃₁₃ of 1.37 (95%CI = 1.22–1.54) (Table 1). For ER-negative invasive CBC, the HR per SD was 0.92 (95%CI = 0.75–1.12) for PRS₃₁₃ and 1.06 (95%CI = 0.86–1.30) for the ER-negative PRS₃₁₃.

Sensitivity analysis using the overall PRS₃₁₃ showed a HR per SD of 1.24 (95%CI = 1.16–1.32) for invasive CBC risk. When we used time since first breast cancer as the timescale, we found similar results (HR per SD = 1.25, 95%CI = 1.18–1.33). Meta-analysis of country-specific effects showed a HR per SD of 1.25 (95%CI = 1.18–1.33) for CBC risk by PRS₃₁₃ (Figure S3).

The association between the PRS₃₁₃ and CBC risk did not change when adjusting for characteristics of the individual, tumor, or treatment, nor when excluding studies oversampling case subjects with a family history (Table S6). When considering potential modifiers of the effect of the PRS₃₁₃ on CBC risk (Table 2), we found that the HR was the lowest in women aged <40 years at first breast cancer diagnosis (HR per SD = 1.13; 95%CI = 0.98–1.31) and tended to increase with age, although these effects were not statistically significant ($P_{\text{heterogeneity}} = 0.26$; $P_{\text{trend}} = 0.05$). We found no indication for effect modification by family history ($P_{\text{heterogeneity}} = 0.63$), morphology ($P_{\text{heterogeneity}} = 0.14$), ER status ($P_{\text{heterogeneity}} = 0.13$), PR status ($p = 0.26$), HER2 status ($P_{\text{heterogeneity}} = 0.42$), chemotherapy ($P_{\text{heterogeneity}} = 0.60$), endocrine therapy ($P_{\text{heterogeneity}} = 0.79$), or radiotherapy ($P_{\text{heterogeneity}} = 0.40$) (Table 2).

The C-index was 0.563 (95%CI = 0.547–0.586) for the model only including PRS₃₁₃, 0.605 (95%CI = 0.591–0.629)

Table 2. Association between the 313-Variant PRS (PRS₃₁₃) and Contralateral Breast Cancer Risk for Subgroups

Subgroups	No. of Patients	No. of CBC	HR per Unit SD ^{a,b}	95%CI	p Value	P _{hetero-geneity} ^{c,d}	P _{trend} ^{c,e}
All patients	56,068	1,027	1.25	1.18–1.33	<.001	-	-
Age at First Breast Cancer Diagnosis (Years)						.26	.05
<40	5,877	171	1.13	0.98–1.31	.09		
40–49	11,928	265	1.25	1.11–1.41	<.001		
50–59	16,882	320	1.22	1.09–1.36	<.001		
60+	21,381	271	1.36	1.21–1.52	<.001		
Family History (First Degree Relative)						.63	-
No	33,623	618	1.26	1.16–1.36	<.001		
Yes	10,369	302	1.22	1.09–1.36	<.001		
Morphology						.14	-
Ductal	37,324	621	1.21	1.12–1.31	<.001		
Lobular	5,878	118	1.32	1.10–1.59	.002		
Mixed (ductal and lobular)	2,174	46	1.52	1.15–2.02	.004		
Other	3,344	70	1.20	0.96–1.50	.11		
ER Status						.13	-
Negative	9,527	194	1.13	0.98–1.30	.08		
Positive	38,090	670	1.28	1.19–1.38	<.001		
PR Status						.26	-
Negative	13,098	244	1.16	1.03–1.32	.02		
Positive	27,044	554	1.27	1.17–1.38	<.001		
HER2 Status						.42	-
Negative	23,787	352	1.29	1.17–1.44	<.001		
Positive	4,969	60	1.45	1.13–1.85	.004		
(Neo)adjuvant Chemotherapy						.60	-
No	18,110	361	1.28	1.16–1.42	<.001		
Yes	18,559	363	1.24	1.12–1.37	<.001		
(Neo)adjuvant Endocrine Therapy						.79	-
No	10,781	242	1.28	1.13–1.44	<.001		
Yes	27,322	460	1.30	1.19–1.43	<.001		
Radiotherapy						.40	-
No	11,023	188	1.33	1.15–1.53	<.001		
Yes	29,142	617	1.24	1.15–1.34	<.001		

Abbreviations: PRS, polygenic risk score; No., number; CBC, contralateral breast cancer; HR, hazard ratio; CI, confidence interval; ER, estrogen receptor; PR, progesterone receptor; HER2, human epidermal growth factor receptor 2.

^aHR for CBC risk by unit SD of PRS₃₁₃. All analyses were performed with attained age as timescale.

^bCoefficients to construct the PRS₃₁₃ are shown in Table S3. The PRS₃₁₃ was standardized by standard deviation = 0.61, in line with Mavaddat et al.⁷

^cThe interaction between the PRS₃₁₃ and each subgroup was tested in different models including the standardized PRS₃₁₃, modifier, and interaction. Patients with unknown values were excluded from these analyses. Since attained age was used as timescale in all models, the model with age at first breast cancer only included the PRS₃₁₃ and interaction.

^dP for interaction based on test for heterogeneity across categories.

^eP for interaction based on a trend test with age as continuous variable.

for the model only including other risk factors, and 0.623 (95%CI = 0.608–0.645) for the complete model (Table 3).

Absolute Risks

Based on the HR estimates for PRS₃₁₃, the predicted CBC risk by age 80 years was 12.4% at the 10th percentile of

Table 3. Discriminatory Ability (C-Index) of the 313-Variant PRS (PRS₃₁₃) and Other Risk Factors for Contralateral Breast Cancer Risk in the European Cohort

	C-Index (95%CI) ^{a,b}
Model 1: PRS ₃₁₃ ^c alone	0.563 (0.547–0.586)
Model 2: Other risk factors ^d	0.605 (0.591–0.629)
Model 3: PRS ₃₁₃ ^c + other risk factors ^d	0.623 (0.608–0.645)

Abbreviations: PRS, polygenic risk score; CI, confidence interval.

^aThe Harrell's C-index was obtained by the STATA `stcox` postestimation command "estat concordance," using time since first breast cancer on the time-scale without taking delayed entry (prevalent cases) into account. We did not consider delayed entry since no standard performance measures are currently available in the statistical literature to account for left-truncated follow-up time. The median of delayed entry was 0.4 years (standard deviation = 2.7) in our study.

^bThe 95% CIs were obtained by use of the `somersd` package in STATA.

^cCoefficients to construct the PRS₃₁₃ are shown in Table S3. The PRS₃₁₃ was standardized by SD = 0.61, in line with Mavaddat et al.⁷

^dIncluding age at first diagnosis, year of first diagnosis, family history for breast cancer in a first degree relative, and clinical characteristics of the first breast cancer (nodal status, tumor size, differentiation grade, morphology, estrogen receptor status, human epidermal growth factor receptor 2 status, chemotherapy, endocrine therapy, radiotherapy).

the PRS₃₁₃, compared with 20.5% at the 90th percentile of the PRS₃₁₃ (Figure 2), accounting for death as competing risk. When death was not taken into account as competing risk, the corresponding predicted risks by age 80 were 17.0% at the 10th percentile and 27.9% at the 90th percentile of the PRS₃₁₃ (Figure S4). Table 4 shows the 5- and 10-year cumulative CBC risks by PRS₃₁₃ for different age groups, accounting for death as competing risk (Table S7 shows results without competing risks).

European and Asian (Case-Case Series) Logistic Regression Analyses

Figure 3 shows the distribution of the PRS₃₁₃ per SD in the European case-case series. Median PRS₃₁₃ was -0.4 (interquartile range [IQR] = 1.35) for control women without any diagnosis of breast cancer (N = 81,000), 0.2 (IQR = 1.36) for women with unilateral breast cancer (N = 62,830), and 0.5 (IQR = 1.40) for women with CBC (N = 3,607). The OR for unilateral breast cancer per SD of the PRS₃₁₃, compared to control women, was 1.82 (95%CI = 1.80–1.84) (Table S8). The OR for CBC per SD of PRS₃₁₃, compared to unilateral breast cancer, was 1.30 (95%CI = 1.26–1.35).

In sensitivity analyses, the OR per SD of PRS₃₁₃ was 1.27 (95%CI = 1.21–1.33) for metachronous CBC and the OR per SD was 1.29 (95%CI = 1.24–1.33) for invasive CBC, compared to unilateral breast cancer. When analyses were restricted to the validation set of Mavaddat et al.,⁷ the OR for unilateral breast cancer per SD of the PRS₃₁₃ was 1.67 (95%CI = 1.59–1.76) compared to control women, and the OR for CBC per SD of PRS₃₁₃ was 1.39 (95%CI = 1.13–1.70) compared to unilateral breast cancer (Table S8).

For women of Asian descent, the OR for unilateral breast cancer per SD of the PRS₃₁₃ was 1.56 (95%CI = 1.52–1.60)

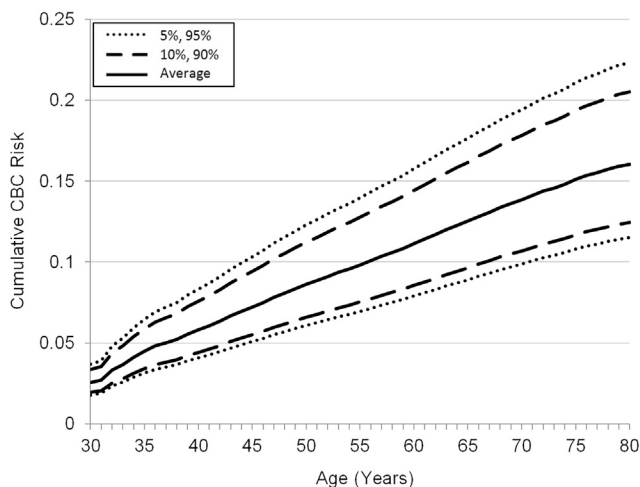


Figure 2. Predicted Contralateral Breast Cancer Risk by Percentile of the 313-Variant PRS (PRS₃₁₃) with Death as Competing Risk Coefficients to construct the PRS₃₁₃ are shown in Table S3. The PRS₃₁₃ was standardized by SD = 0.61, in line with Mavaddat et al.⁷ The CBC incidences were calculated based on incidence data from the Netherlands Cancer Registry¹ and relative risks estimated as described in the Material and Methods. PRS, polygenic risk score; CBC, contralateral breast cancer.

compared to control women, and the OR for CBC per SD of PRS₃₁₃ was 1.15 (95%CI = 1.02–1.29) compared to women with unilateral breast cancer (Table S8).

Discussion

Previous studies have shown that a PRS, summarizing the effects of common germline variants, can be used to stratify women with respect to their risk to develop a primary breast cancer.^{6–9} In this study, we observed a clear association between the PRS₃₁₃ and CBC risk in women of both European and Asian ancestry. The association was observed in both the case-case series and the European cohort. The HRs per SD of CBC for women at the 10th and 90th percentile of the continuous predicted PRS₃₁₃ were 0.75 and 1.33, respectively, compared to the 50th percentile. This translates to absolute risks at the 10th and the 90th percentile of the PRS₃₁₃ of 12.4% and 20.5%, respectively, by age 80 years. We estimated a C-index for the PRS₃₁₃, summarizing its discriminatory ability, of 0.563 in the European cohort.

One previous study has investigated the effect of a PRS, including 67 variants, and CBC risk.¹⁰ This study found a risk ratio of 1.75 (95%CI = 1.41–2.18) for women in the upper quartile of the PRS compared with women in the lowest quartile. To facilitate comparison, we performed a similar analysis in our case-case series, showing an OR of 1.98 (95%CI = 1.79–2.18), adjusted for country and age at first diagnosis, for women in the upper quartile of the PRS₃₁₃. This indicates that the PRS₃₁₃ improves stratification relative to PRSs including fewer variants. Moreover, in our European cohort, the C-index for the PRS alone

Table 4. 5- and 10-Year Cumulative Risks of Contralateral Breast Cancer by the 313-Variant PRS (PRS₃₁₃) for Different Age Groups with Death as Competing Risk

Age at First Breast Cancer Diagnosis (years)	5-Year Cumulative CBC Risks (%) Range by Age					10-Year Cumulative CBC risks (%) Range by Age				
	5 th Percentile PRS ₃₁₃	10 th Percentile PRS ₃₁₃	50 th Percentile PRS ₃₁₃	90 th Percentile PRS ₃₁₃	95 th Percentile PRS ₃₁₃	5 th Percentile PRS ₃₁₃	10 th Percentile PRS ₃₁₃	50 th Percentile PRS ₃₁₃	90 th Percentile PRS ₃₁₃	95 th Percentile PRS ₃₁₃
30–34	1.9–3.1	2.1–3.4	2.7–4.5	3.6–5.9	4.0–6.5	3.1–4.1	3.4–4.5	4.5–5.9	5.9–7.7	6.5–8.5
35–39	0.8–2.1	0.9–2.3	1.2–3.0	1.5–3.9	1.7–4.3	2.1–3.5	2.3–3.8	3.0–5.0	3.9–6.6	4.3–7.2
40–44	1.5–2.8	1.7–3.1	2.2–4.1	2.9–5.3	3.2–5.9	2.8–4.6	3.1–5.0	4.1–6.6	5.3–8.6	5.9–9.4
45–49	1.4–2.5	1.5–2.7	2.0–3.6	2.6–4.7	2.9–5.2	2.5–3.9	2.7–4.3	3.6–5.6	4.7–7.4	5.2–8.1
50–54	1.4–2.8	1.5–3.0	1.9–4.0	2.6–5.2	2.8–5.8	2.8–4.5	3.0–4.9	4.0–6.4	5.2–8.4	5.8–9.3
55–59	1.6–3.1	1.8–3.4	2.3–4.5	3.1–5.9	3.4–6.5	3.1–4.8	3.4–5.2	4.5–6.9	5.9–9.0	6.5–9.9
60–64	1.7–3.3	1.9–3.6	2.5–4.7	3.3–6.2	3.6–6.8	3.3–5.0	3.6–5.4	4.7–7.1	6.2–9.3	6.8–10.2
65–70	1.5–3.2	1.6–3.5	2.1–4.6	2.8–6.1	3.1–6.7	3.2–4.1	3.5–4.5	4.6–5.9	6.1–7.7	6.7–8.5

Abbreviations: PRS, polygenic risk score; CBC, contralateral breast cancer. Coefficients to construct the PRS₃₁₃ are shown in Table S3. The PRS₃₁₃ was standardized by SD = 0.61, in line with Mavaddat et al.⁷ The CBC incidences for each age group were calculated based on incidence data from the Netherlands Cancer Registry¹ and relative risks estimated as described in the Material and Methods. Death was taken into account as competing risk.

improved from 0.547 (95%CI = 0.536–0.575) for the previously reported PRS₇₇⁶ to 0.563 (95%CI = 0.547–0.586) for the PRS₃₁₃.

We found no evidence that the association between the PRS₃₁₃ and CBC risk was confounded by family history, adjuvant therapy, morphology, age, or tumor receptor status of the first breast cancer, nor that there was effect modification by those factors. The absence of notable effect modification is in line with the abovementioned study of a 67-variant PRS and CBC risk; no heterogeneity in association was found by age, family history, morphology, ER status, and adjuvant treatment.¹⁰

To provide an external validation of our findings, we examined data from UK Biobank, which includes many

women diagnosed with breast cancer with data available on the PRS₃₁₃ (Supplemental Note). Unfortunately, UK Biobank has no information available on the laterality of the tumor, and it is, therefore, not possible to distinguish between contralateral and ipsilateral breast cancers. We therefore performed analyses using any second breast cancer as the endpoint. This secondary analysis did confirm the association between the PRS₃₁₃ and second breast cancer risk (HR per SD = 1.13, 95%CI = 1.01–1.27), but with a lower estimate than in our European cohort. The lower estimate may be explained by the inclusion of the ipsilateral breast cancers, which may be more likely to be recurrences than new primary breast cancers compared to CBCs. Indeed, when we used ipsilateral breast cancer as the outcome in our European cohort, we found no association with the PRS₃₁₃ (HR = 1.02, 95%CI = 0.90–1.15).

The association between the PRS₃₁₃ and CBC risk (OR per SD = 1.30; 95%CI = 1.26–1.35) in the BCAC database was weaker (expressed in terms of an OR) than was found for first breast cancer among independent prospective studies (OR per SD = 1.61; 95%CI = 1.57–1.65). Under a simple polygenic model, the relative risk would be expected to be similar for the second breast cancer. The attenuated estimate for CBC might however be explained by several factors. Some attenuation of the estimate might have been due to dilution in the end-point definition, i.e., if some of the CBCs were metastases. Previous studies investigating the clonal relatedness of first breast cancers and CBCs using tumor sequencing have shown that 6%–12% of CBCs represent metastases.^{18,19} This hypothesis would be consistent with our finding of a slightly stronger association between the PRS₃₁₃ and late CBCs, diagnosed >5 years after the first breast cancer, than for early CBCs, diagnosed ≥5 years after the first cancer, since the latter are more likely to be metastases. In addition, 3%–5% of

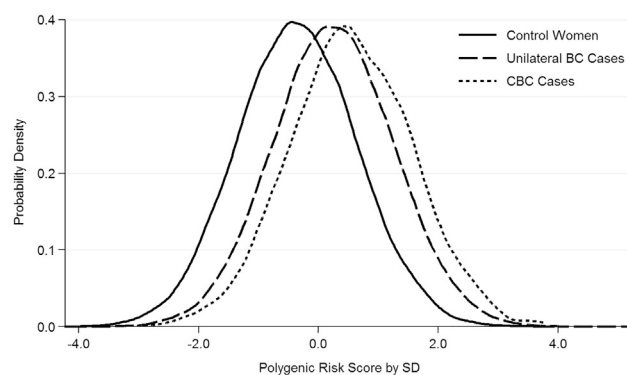


Figure 3. Distribution of the 313-Variant PRS (PRS₃₁₃) in 62,830 Control Women without Any Diagnosis of Breast Cancer, 81,000 Women with Unilateral Breast Cancer, and 3,607 Women with Contralateral Breast Cancer

Coefficients to construct the PRS₃₁₃ are shown in Table S3. The PRS₃₁₃ was standardized by SD = 0.61, in line with Mavaddat et al.⁷ PRS, polygenic risk score; BC, breast cancer; CBC, contralateral breast cancer; SD, standard deviation.

the women with breast cancer will have a mutation in *BRCA1* or *BRCA2*,^{20,21} who have high CBC risks. It has been shown that the relative risk associated with PRS is lower (for the first breast cancer) for women with a *BRCA1* and *BRCA2* mutation than in the general population,²² diluting the overall relative risk for CBC. More generally, it is possible that the CBC association may be attenuated due to the effect of other, unmeasured, genetic or other risk factors. If the risks are high, case subjects with higher PRS₃₁₃ will have, on average, lower values of other risk factors, due to elimination of the highest risk individuals, again attenuating the CBC association. Finally, given the limited information on family history in our dataset, the estimate could have been biased due to a family history effect not detected in our data.

There was some suggestion that the relative risk associated with PRS₃₁₃ decreased with younger age ($P_{\text{trend}} = 0.05$) and, specifically, was lower for women aged <40 years (HR per SD = 1.13; 95%CI = 0.98–1.31). Interestingly, Mavaddat et al.⁷ also found a lower relative risk below age 40 for first breast cancer. This effect may reflect the different characteristics of breast cancers at young ages, both in terms of germline susceptibility and pathology.^{23,24} For example, the proportion of ER-negative breast cancers is higher at young ages, and the PRS is less predictive for ER-negative disease.^{6,7,24}

In the logistic regression analyses in Asian women, the association between the PRS₃₁₃ and CBC risk was slightly weaker than in European women. This finding is consistent with a recent analysis investigating the association between a 287-variant PRS and first breast cancer risk in the Asian population,²⁵ which showed an attenuated OR in Asian women (OR = 1.52, 95%CI = 1.49–1.56) compared to European women (OR = 1.61, 95%CI = 1.57–1.66). The lower estimate for Asian women might reflect the fact the PRS₃₁₃ was developed in European populations, and the different LD structure in Asians may attenuate the association since the variants in the PRS are likely to be surrogates for the causal variants. Other explanations for the attenuated estimate may be the slightly younger age at first breast cancer diagnosis and the higher proportion ER-negative CBCs in Asian women compared to European women in our study. Finally, the imputation quality for variants was somewhat lower, on average, for the Asian than for the European dataset, with three variants on OncoArray and four variants on ICOGs with an imputation quality score < 0.3 (Table S3). Nevertheless, we included those variants in the PRS for both European and Asian women, to keep the PRS comparable between ethnicities and studies. Future studies including larger numbers of Asian women, and women of other ethnicities, are needed to generate population-specific PRSs and to validate our findings in these groups.

A major strength of this study is the very large sample size in the BCAC dataset, including genotype information for ~150,000 women and a large number of CBC

events. A limitation of this study is missing data on the patient, tumor, and treatment characteristics, which reduces the power of the multivariable Cox regression analyses and interaction analyses. In addition, registration of CBC was not complete; the 10-year cumulative CBC incidence was 2.2% in the BCAC dataset, compared to 3.8% using complete data from the Netherlands Cancer Registry.¹ For this reason, we estimated relative risk estimates using the BCAC data and applied these to external registry data to obtain absolute risk estimates. The under-reporting of CBC should not bias our HR estimates, given that the event rate is low and reporting of CBC is unlikely to be related to the PRS₃₁₃. Moreover, we reran the cohort analysis in the subset of countries with a 10-year cumulative CBC incidence $\geq 3.0\%$ in the BCAC dataset, and the estimates were very similar to the main analyses (HR per SD = 1.23, 95%CI = 1.14–1.33) (Figure S3).

In conclusion, the PRS₃₁₃ is predictive for the development of CBC. We found no evidence for confounding or effect modification by other previously established CBC risk factors. The PRS₃₁₃ is therefore likely to be an independent risk factor for CBC. Since the predictive ability of the PRS on its own is modest, it should be combined with other breast cancer risk factors to provide more useful CBC risk prediction models. More accurate risk prediction will help identify women at high CBC risk who will benefit from additional surveillance and/or risk reducing mastectomy, and equally important, to identify those women at low risk in order to avoid unnecessary surgeries.

Data and Code Availability

Data used in this manuscript may be requested through the original providers. Data of the Breast Cancer Association Consortium may be requested for non-profit research through an application procedure with the Breast Cancer Association Consortium. Data of the UK Biobank needs to be requested through UK Biobank.

Supplemental Data

Supplemental Data can be found online at <https://doi.org/10.1016/j.ajhg.2020.09.001>.

Declaration of Interests

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Web Resources

Breast Cancer Association Consortium, <http://bcac.ccge.medschl.cam.ac.uk/bcacdata/>
UK Biobank, <https://www.ukbiobank.ac.uk/researchers/>

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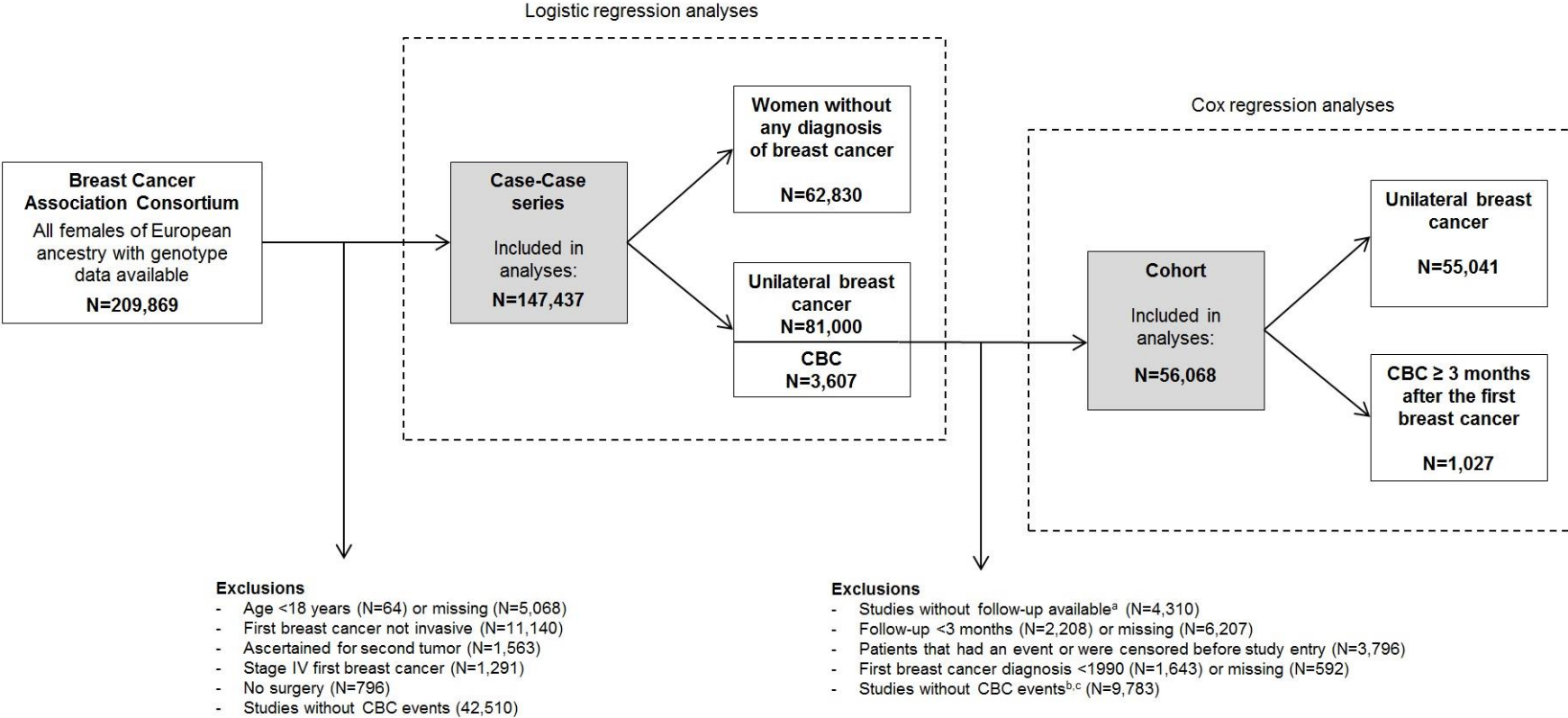
Supplemental Data

Breast Cancer Polygenic Risk Score and Contralateral Breast Cancer Risk

Iris Kramer, Maartje J. Hooning, Nasim Mavaddat, Michael Hauptmann, Renske Keeman, Ewout W. Steyerberg, Daniele Giardiello, Antonis C. Antoniou, Paul D.P. Pharoah, Sander Canisius, Zumuruda Abu-Ful, Irene L. Andrulis, Hoda Anton-Culver, Kristan J. Aronson, Annelie Augustinsson, Heiko Becher, Matthias W. Beckmann, Sabine Behrens, Javier Benitez, Marina Bermisheva, Natalia V. Bogdanova, Stig E. Bojesen, Manjeet K. Bolla, Bernardo Bonanni, Hiltrud Brauch, Michael Bremer, Sara Y. Brucker, Barbara Burwinkel, Jose E. Castelao, Tsun L. Chan, Jenny Chang-Claude, Stephen J. Chanock, Georgia Chenevix-Trench, Ji-Yeob Choi, Christine L. Clarke, NBCS Collaborators, J. Margriet Collée, Fergus J. Couch, Angela Cox, Simon S. Cross, Kamila Czene, Mary B. Daly, Peter Devilee, Thilo Dörk, Isabel dos-Santos-Silva, Alison M. Dunning, Miriam Dwek, Diana M. Eccles, D. Gareth Evans, Peter A. Fasching, Henrik Flyger, Manuela Gago-Dominguez, Montserrat García-Closas, José A. García-Sáenz, Graham G. Giles, David E. Goldgar, Anna González-Neira, Christopher A. Haiman, Niclas Håkansson, Ute Hamann, Mikael Hartman, Bernadette A.M. Heemskerk-Gerritsen, Antoinette Hollestelle, John L. Hopper, Ming-Feng Hou, Anthony Howell, ABCTB Investigators, kConFab Investigators, Hidemi Ito, Milena Jakimovska, Anna Jakubowska, Wolfgang Janni, Esther M. John, Audrey Jung, Daehee Kang, C. Marleen Kets, Elza Khusnutdinova, Yon-Dschun Ko, Vessela N. Kristensen, Allison W. Kurian, Ava Kwong, Diether Lambrechts, Loic Le Marchand, Jingmei Li, Annika Lindblom, Jan Lubiński, Arto Mannermaa, Mehdi Manoochehri, Sara Margolin, Keitaro Matsuo, Dimitrios Mavroudis, Alfons Meindl, Roger L. Milne, Anna Marie Mulligan, Taru A. Muranen, Susan L. Neuhausen, Heli Nevanlinna, William G. Newman, Andrew F. Olshan, Janet E. Olson, Håkan Olsson, Tjoung-Won Park-Simon, Julian Peto, Christos Petridis, Dijana Plaseska-Karanfilska, Nadege Presneau, Katri Pylkäs, Paolo Radice, Gad Rennert, Atocha Romero, Rebecca Roylance, Emmanouil Saloustros, Elinor J. Sawyer, Rita K. Schmutzler, Lukas Schwentner, Christopher Scott, Mee-Hoong See, Mitul Shah, Chen-Yang Shen, Xiao-Ou Shu, Sabine Siesling, Susan Slager, Christof Sohn, Melissa C. Southey, John J. Spinelli, Jennifer Stone, William J. Tapper, Maria Tengström, Soo Hwang Teo, Mary Beth Terry, Rob A.E.M. Tollenaar, Ian Tomlinson, Melissa A. Troester, Celine M. Vachon, Chantal van Ongeval, Elke M. van Veen, Robert Winqvist, Alicja Wolk, Wei Zheng, Argyrios Ziogas, Douglas F. Easton, Per Hall, and Marjanka K. Schmidt

Supplemental Figures

Figure S1A. Overview of the selection of women with breast cancer and control women for the European series



Abbreviations: CBC = contralateral breast cancer

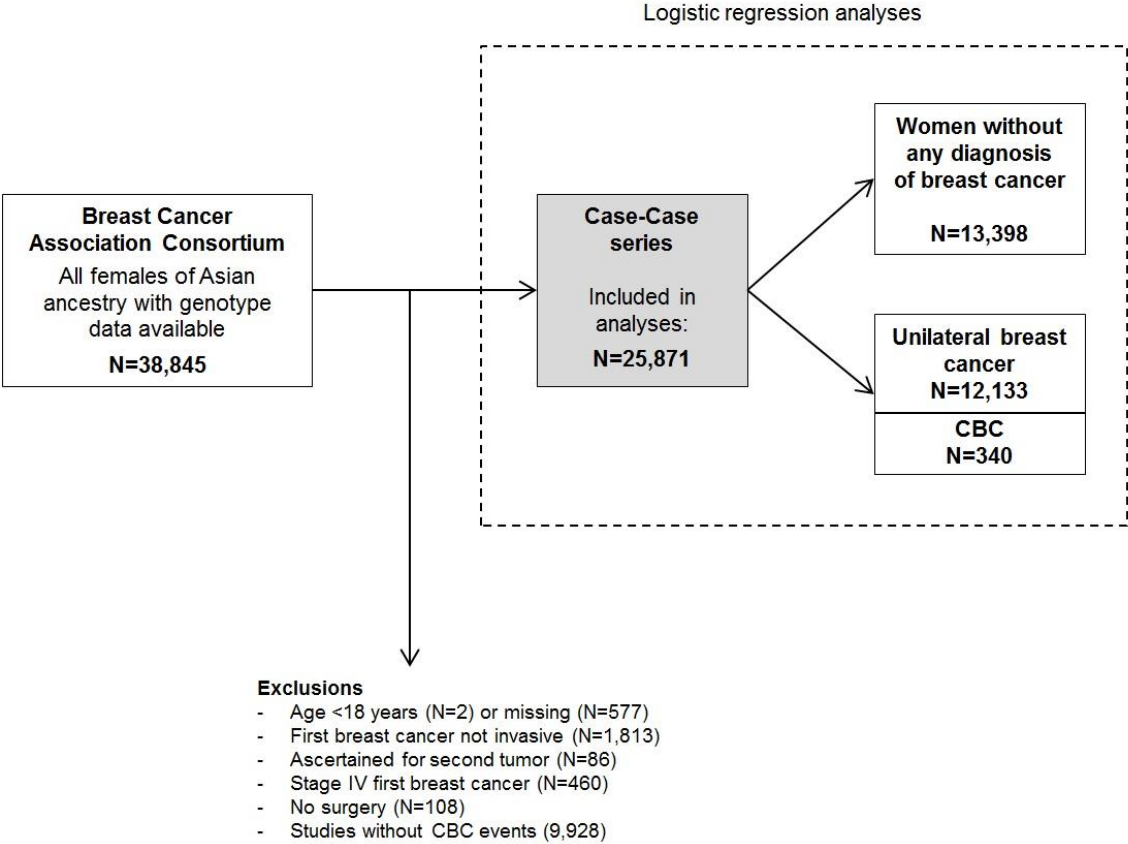
For a complete overview of all studies see Table S1

^a Excluded studies: CBCS, GLACIER, HMBCS, TNBCC

^b Excluded studies: BCFR-NY, BCFR-UTAH, CNIO-BCS, DIETCOMPLYF, FHRISK, GESBC, HABCS, HUBCS, ICICLE, KBCP, MCCS, MMHS, NCBCS, PREFACE, SUCCESSB, SUCCESSC

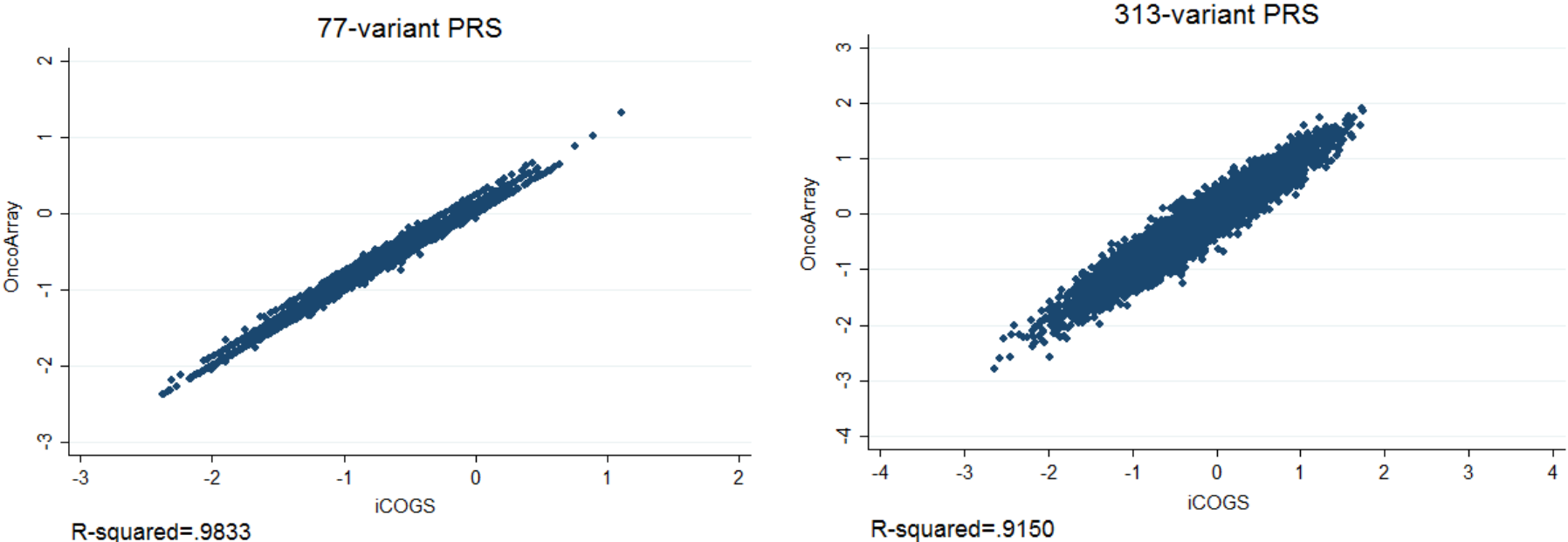
^c These studies dropped out because for these analyses the definition of CBC is based on the criteria that the CBC was diagnosed at least three months after the first breast cancer diagnosis

Figure S1B. Overview of the selection of women with breast cancer and control women for Asian series



Abbreviations: CBC = contralateral breast cancer

Figure S2. Correlation of total variant scores between the iCOGS array and OncoArray for the 77-variant PRS and the 313-variant PRS^{a,b}

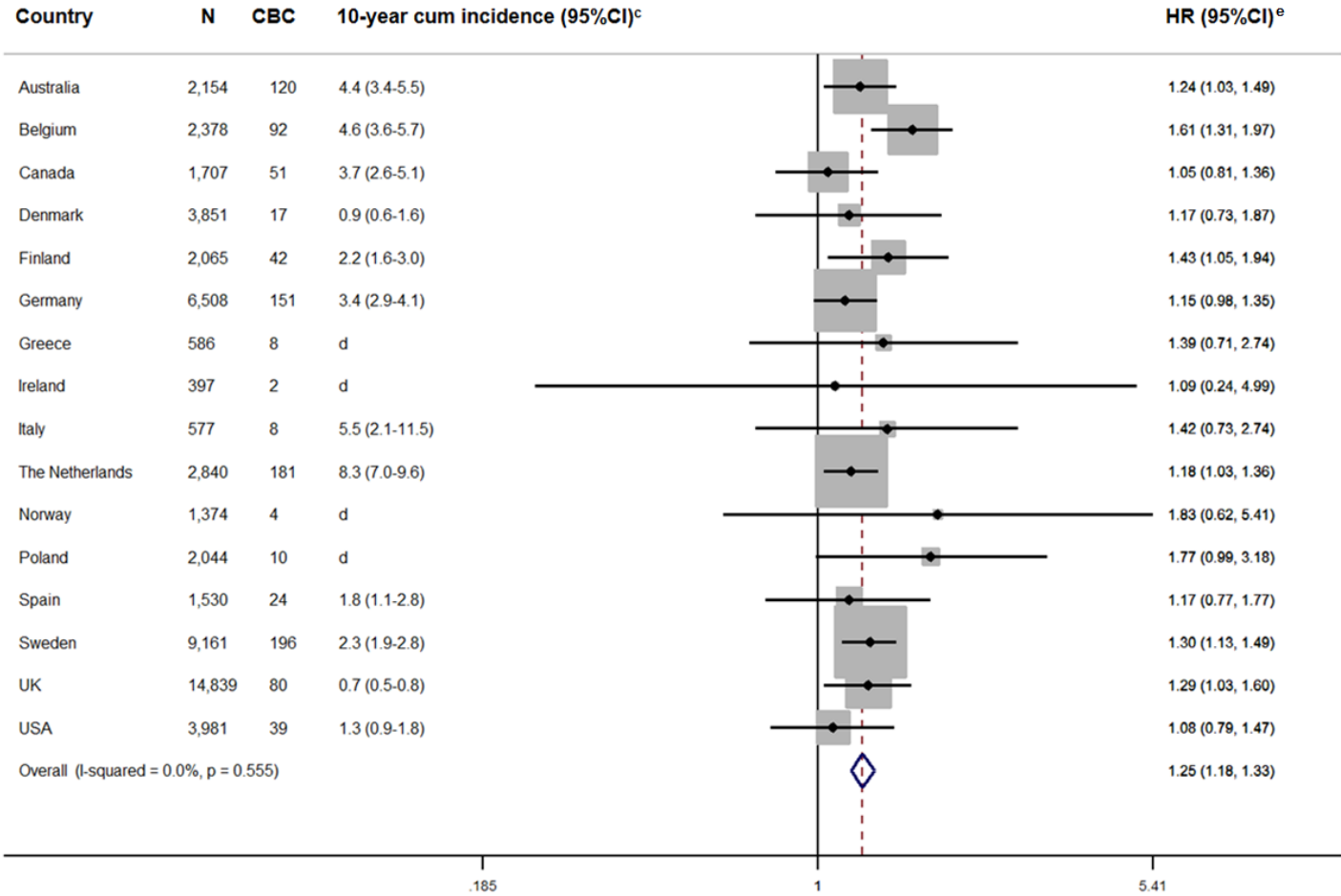


Abbreviations: PRS = polygenic risk score, SD = standard deviation

^aWe evaluated consistency between iCOGS and OncoArray using the intraclass correlation coefficient (ICC), showing a ICC of 0.99 (95%CI=0.99-0.99) for the PRS₇₇, and an ICC of 0.96 (95%CI=0.95-0.96) for the PRS₃₁₃, based on N=9,071 observations

^bCoefficients to construct the PRSs are shown in Table S3. The PRSs were standardized by the same SD as was used by Mavaddat et al.¹. The SD was 0.45 for overall breast cancer PRS₇₇, and 0.61 for overall breast cancer PRS₃₁₃

Figure S3. Forest plot of the association between the 313-variant PRS and contralateral breast cancer risk by country^{a,b}



Abbreviations: PRS = polygenic risk score, N = number of women, CBC = contralateral breast cancer, cum = cumulative, CI = confidence interval, HR = hazard ratio, SD = standard deviation

Fixed effect meta-analysis was used to calculate I-squared and P-value for heterogeneity

^a Republic of North Macedonia was left out this plot because of a too small sample size (N=76 women including N=2 CBC events)

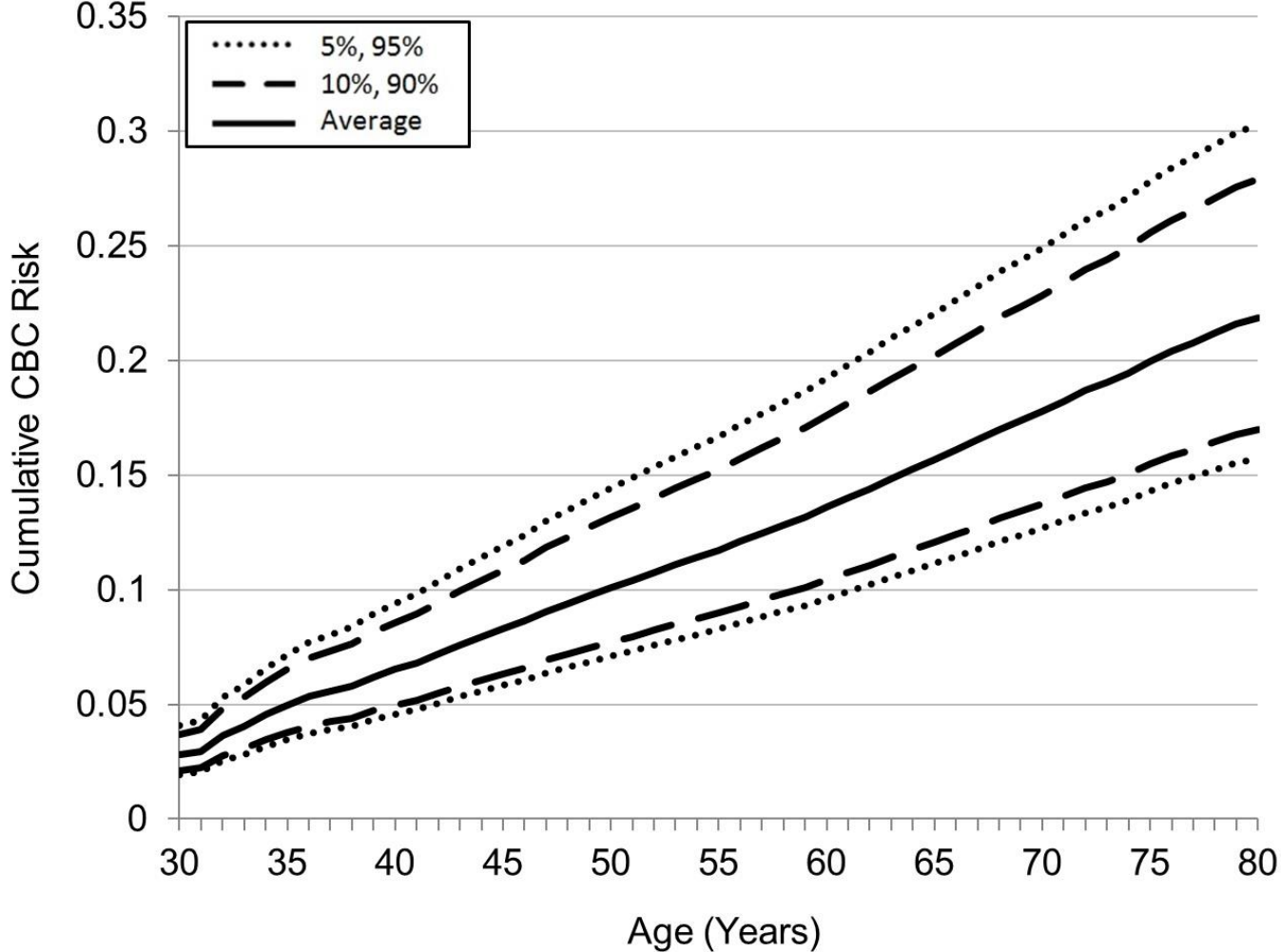
^b Coefficients to construct the PRS₃₁₃ are shown in Table S3. The PRS₃₁₃ was standardized by SD=0.61, in line with Mavaddat et al.¹

^c The 10-year cumulative incidence of CBC was estimated with time since first breast cancer as time scale, and distant metastases (where available) and death as competing risks

^d Follow-up too short for calculating 10-year cumulative incidence

^e HR per SD. The analyses were performed with attained age as the time scale

Figure S4. Predicted contralateral breast cancer risk by percentile of the 313-variant PRS (PRS₃₁₃)



Abbreviations: PRS = polygenic risk score, CBC = contralateral breast cancer
Coefficients to construct the PRS₃₁₃ are shown in Table S3. The PRS₃₁₃ was standardized by SD=0.61, in line with Mavaddat et al¹. The CBC incidences were calculated based on incidence data from the Netherlands Cancer Registry² and relative risks estimated as described in the Material and Methods. In contrast to Figure 2, death was not taken into account as competing risk.

Supplemental Tables

Table S1. Study characteristics of included studies of the Breast Cancer Association Consortium

Table S2. Studies and samples included in the analyses using the case-case series, cohort, and validation set

Studies	European									Asian		
	Case-case series N studies = 62			Cohort N studies = 42		Validation set N studies = 24			Case-case series N studies = 8			
	Control women ^a	Unilateral BC	CBC	Unilateral BC	CBC	Control women ^a	Unilateral BC	CBC	Control women ^a	Unilateral BC	CBC	
ABCFS	738	1,149	127	1,021	93	-	-	-	-	-	-	
ABCS	1,567	1,047	54	519	14	-	-	-	-	-	-	
ABCS-F	0	861	91	363	17	-	-	-	-	-	-	
ABCTB	375	900	17	708	1	74	180	8	-	-	-	
BBCC	711	845	58	766	6	49	56	5	-	-	-	
BBCS	1,768	1,266	80	466	1	-	-	-	-	-	-	
BCEES	-	-	-	-	-	166	133	0	-	-	-	
BCFR-NY	27	340	61	-	-	-	-	-	-	-	-	
BCFR-PA	0	104	14	69	4	-	-	-	-	-	-	
BCFR-UTAH	0	13	87	-	-	-	-	-	-	-	-	
BCINIS	-	-	-	-	-	144	262	0	-	-	-	
BIGGS	49	713	50	395	2	-	-	-	-	-	-	
BREOGAN	725	1,245	19	1,233	15	145	238	4	-	-	-	
BSUCH	1,122	900	36	727	3	-	-	-	-	-	-	
CBCS	817	530	21	-	-	163	105	4	170	238	10	
CCGP	321	598	19	578	8	66	125	7	-	-	-	
CGPS	5,250	4,135	60	3,834	17	142	227	3	-	-	-	
CNIO-BCS	829	742	5	-	-	-	-	-	-	-	-	
CTS	-	-	-	-	-	115	220	0	-	-	-	
DIETCOMPLYF	0	704	1	-	-	-	-	-	-	-	-	
FHRISK	0	119	2	-	-	-	-	-	-	-	-	
GC-HBOC	1,732	2,690	230	1,406	47	-	-	-	-	-	-	
GENICA	711	869	26	869	1	56	89	2	-	-	-	
GESBC	181	303	3	-	-	-	-	-	-	-	-	
GLACIER	0	1,733	230	-	-	-	-	-	-	-	-	
HABCS	863	774	84	-	-	173	141	6	-	-	-	
HCSC	0	362	13	273	9	-	-	-	-	-	-	
HEBCS	1,060	1,632	116	1,578	41	-	-	-	-	-	-	
HERPACC	-	-	-	-	-	-	-	-	1,659	756	18	
HKBCS	-	-	-	-	-	-	-	-	451	403	12	
HMBCS	345	729	28	-	-	-	-	-	-	-	-	
HUBCS	116	198	2	-	-	-	-	-	-	-	-	
ICICLE	1	138	12	-	-	-	-	-	-	-	-	
KARBAC	0	761	46	443	32	-	-	-	-	-	-	
KARMA	5,981	2,314	96	2,188	33	597	185	10	-	-	-	
KBCP	431	516	9	-	-	-	-	-	-	-	-	
KCONFAB/AOCS	898	397	83	305	26	-	-	-	-	-	-	
LMBC	1,821	3,016	208	2,286	92	87	142	14	-	-	-	
MABCS	88	80	9	74	2	-	-	-	-	-	-	

MARIE	2,066	1,540	115	1,535	53	-	-	-	-	-	-	
MBCSG	766	1,015	150	569	8	-	-	-	-	-	-	
MCBCS	2,093	1,999	59	1,903	6	35	96	3	-	-	-	
MCCS	1,207	1,034	2	-	-	142	86	0	-	-	-	
MEC	1,123	1,016	38	988	23	-	-	-	-	-	-	
MISS	1,529	582	6	563	3	304	83	0	-	-	-	
MMHS	1,635	273	4	-	-	320	48	4	-	-	-	
MYBRCA	-	-	-	-	-	-	-	-	4,197	3,652	105	
NBCS	212	2,334	31	1,370	4	-	-	-	-	-	-	
NBHS	-	-	-	-	-	122	79	0	-	-	-	
NC-BCFR	150	614	69	602	5	-	-	-	52	391	33	
NCBCS	1,006	1,988	42	-	-	-	-	-	-	-	-	
OBCS	414	467	10	445	1	-	-	-	-	-	-	
OFBCR	728	1,908	143	1,656	51	-	-	-	-	-	-	
ORIGO	0	1,090	89	1,053	69	132	134	15	-	-	-	
PBCS	2,082	1,719	40	1,625	9	331	215	2	-	-	-	
PKARMA	5,435	4,81	277	4,685	124	1	4	0	-	-	-	
POSH	0	1,069	19	1,063	16	-	-	-	-	-	-	
PREFACE	0	2,73	90	-	-	-	-	-	-	-	-	
PROCAS	1,647	488	9	422	3	-	-	-	-	-	-	
RBCS	0	873	152	724	81	-	-	-	-	-	-	
SASBAC	1,378	1,118	22	1,086	5	-	-	-	-	-	-	
SBCS	848	748	14	691	1	-	-	-	-	-	-	
SEARCH	9,056	12,423	118	12,117	59	197	628	0	-	-	-	
SEBCS	-	-	-	-	-	-	-	-	2,236	2,080	21	
SGBCC	-	-	-	-	-	-	-	-	4,141	1,250	124	
SKKDKFZS	29	1,084	71	1,054	41	-	-	-	-	-	-	
SMC	-	-	-	-	-	141	244	0	-	-	-	
SUCCESSB	0	438	2	-	-	-	-	-	-	-	-	
SUCCESSC	0	2,807	29	-	-	-	-	-	-	-	-	
SZBCS	489	676	6	409	1	-	-	-	-	-	-	
TNBCC	152	1,037	2	-	-	-	-	-	-	-	-	
TWBCS	-	-	-	-	-	-	-	-	492	1,250	17	
UCIBCS	258	397	1	380	1	51	61	7	-	-	-	
Total	62,830	81,000	3,607	55,041	1,027	3,753	3,781	94	13,398	12,133	340	
Characteristics												
Invasiveness	in situ	-	excluded	361	excluded	104	-	3 ^b	7	-	excluded	67
	invasive	-	79,876	2,200	54,675	670	-	3,777	60	-	11,929	209
	unknown	-	1,124	1,046	366	253	-	1	27	-	204	64
ER status	negative	-	13,828	446	9,333	105	-	766	8	-	3,457	54
	positive	-	52,238	2,048	37,420	289	-	3,001	47	-	7,826	163
	unknown	-	14,934	1,113	8,288	633	-	14	39	-	850	123

Abbreviations: BC = breast cancer, CBC = contralateral breast cancer, ER = estrogen receptor

^a Without any diagnosis of breast cancer

^b Due to the use of a new freeze of the BCAC data, N=3 breast cancers were now defined as in situ, which had previously been defined as invasive; the original validation dataset contained data of two additional studies¹

Table S3. Variant information and breast cancer risk coefficients for the 77-variant PRS, 313-variant PRS, and ER-specific PRSs; previously published in Mavaddat et al.^{1;3}

Table S4. Patient, tumor, and treatment characteristics of all women diagnosed with first invasive breast cancer since 1990 (European cohort)

Characteristics	Number of women (%)^a
Total	56,068 (100)
Median age at first diagnosis in years (range)	56 (18-98)
Year of diagnosis	
1990-1994	3,029 (5.4)
1995-1999	10,153 (18.1)
2000-2004	18,484 (33.0)
2005-2009	17,575 (31.3)
2010-2015	6,827 (12.2)
Family history (first degree relative)	
no	33,623 (76.4)
yes	10,369 (23.6)
unknown	12,076
Nodal status	
negative	29,070 (61.9)
positive	17,903 (38.1)
unknown	9,095
Tumor size, cm	
≤2	28,057 (63.8)
(2, 5]	14,138 (32.2)
>5	1,750 (4.0)
unknown	12,123
Differentiation grade	
I	8,721 (19.5)
II	21,621 (48.3)
III	14,454 (32.3)
unknown	11,272
Morphology	
ductal	37,324 (76.6)
lobular	5,878 (12.1)
mixed (ductal and lobular)	2,174 (4.5)
other	3,344 (6.9)
unknown	7,348

ER-status		
	negative	9,527 (20.0)
	positive	38,090 (80.0)
	unknown	8,451
PR-status		
	negative	13,098 (32.6)
	positive	27,044 (67.4)
	unknown	15,926
HER2-status		
	negative	23,787 (82.7)
	positive	4,969 (17.3)
	unknown	27,312
Surgery		
	yes, breast saving	16,468 (42.3)
	yes, mastectomy	11,315 (29.1)
	yes, type unknown	11,163 (28.7)
	unknown	17,122
(Neo)adjuvant chemotherapy		
	no	18,110 (49.4)
	yes	18,559 (50.6)
	unknown	19,399
(Neo)adjuvant endocrine therapy		
	no	10,781 (28.3)
	yes	27,322 (71.7)
	unknown	17,965
Radiotherapy		
	no	11,023 (27.4)
	yes	29,142 (72.6)
	unknown	15,903

Abbreviations: ER = estrogen receptor, PR = progesterone receptor, HER2 = human epidermal growth factor receptor 2

^a Total may not be 100% because of rounding

Table S5. Association between the 313-variant PRS (PRS₃₁₃) and contralateral breast cancer risk in the European cohort

Percentile categories of the PRS ₃₁₃	No. of women	No. of CBC	HR per unit SD ^a	95%CI	P-value
0 th to 10 th	5,607	65	0.59	0.45-0.78	<.001
10 th to 20 th	5,606	79	0.71	0.55-0.92	.01
20 th to 40 th	11,214	165	0.74	0.60-0.90	.003
40 th to 60 th	11,214	224	1.00	Ref.	-
60 th to 80 th	11,214	208	0.90	0.74-1.08	.25
80 th to 90 th	5,607	121	1.05	0.84-1.31	.69
90 th to 100 th	5,606	165	1.38	1.13-1.69	.002

Abbreviations: PRS = polygenic risk score, No = number, CBC = contralateral breast cancer, HR = hazard ratio, CI = confidence interval, SD = standard deviation

^aThe analysis was performed with attained age as time scale. Coefficients to construct the PRS₃₁₃ are shown in Table S3. The PRS₃₁₃ was standardized by SD=0.61, in line with Mavaddat et al.¹

Table S6. Multivariable Cox regression models of contralateral breast cancer risk by 313-variant PRS (PRS₃₁₃) in all women, all women excluding studies oversampling cases with family history, and those with complete covariate information

	All patients			All women excluding studies oversampling cases with family history			Complete case		
	N=56,068 (CBC=1,027)			N=51,883 (CBC=829)			N=12,065 (CBC=193)		
	HR per unit SD ^a	95%CI	P-value	HR per unit SD ^a	95%CI	P-value	HR per unit SD ^a	95%CI	P-value
<i>Model 1</i> PRS₃₁₃^b	1.25	1.18-1.33	<.001	1.26	1.17-1.34	<.001	1.35	1.17-1.56	<.001
<i>Model 2</i> PRS₃₁₃^b	1.23	1.16-1.31	<.001	1.25	1.17-1.34	<.001	1.33	1.15-1.54	<.001
Family history									
yes vs. no	1.43	1.24-1.64	<.001	1.34	1.13-1.59	.001	1.49	1.06-2.09	.02
unknown vs. no	0.93	0.75-0.16	.54	0.92	0.73-1.16	.47	-	-	-
<i>Model 3</i> PRS₃₁₃^b	1.25	1.18-1.33	<.001	1.26	1.17-1.34	<.001	1.35	1.17-1.56	<.001
Nodal status									
positive vs. negative	1.05	0.91-1.20	.50	1.07	0.92-1.25	.37	1.14	0.85-1.53	.37
unknown vs. no	1.26	1.04-1.53	.02	1.29	1.04-1.60	.02	-	-	-
<i>Model 4</i> PRS₃₁₃^b	1.25	1.18-1.33	<.001	1.26	1.18-1.35	<.001	1.35	1.17-1.56	<.001
Tumor size,									
(2-5] vs. ≤2	1.08	0.92-1.25	.34	1.12	0.95-1.32	.20	0.93	0.68-1.27	.66
>5 vs. ≤2	1.37	0.99-1.89	.06	1.45	1.02-2.07	.04	1.63	0.93-2.85	.09
unknown vs. ≤2	1.23	1.04-1.47	.02	1.14	0.94-1.39	.18	-	-	-
<i>Model 5</i> PRS₃₁₃^b	1.25	1.17-1.33	<.001	1.25	1.17-1.34	<.001	1.35	1.17-1.57	<.001
Differentiation grade									
II vs. I	0.93	0.76-1.13	.45	0.99	0.80-1.24	.94	0.98	0.65-1.48	.93
III vs. I	0.90	0.73-1.12	.35	0.97	0.76-1.24	.81	1.09	0.70-1.69	.69
unknown vs. I	1.20	0.96-1.49	.11	1.45	1.13-1.86	.004	-	-	-
<i>Model 6</i> PRS₃₁₃^b	1.25	1.17-1.33	<.001	1.25	1.17-1.34	<.001	1.33	1.16-1.54	<.001
Morphology									
lobular vs. ductal	1.26	1.03-1.53	.03	1.34	1.08-1.67	.008	1.48	0.99-2.21	.05
mixed (ductal and lobular) vs. ductal	1.28	0.94-1.73	.11	1.36	0.98-1.88	.06	1.48	0.87-2.54	.15
other vs. ductal	1.04	0.81-1.33	.75	0.91	0.66-1.24	.55	1.24	0.69-2.21	.47
unknown vs. ductal	1.77	1.42-2.19	<.001	1.82	1.44-2.30	<.001	-	-	-
<i>Model 7</i> PRS₃₁₃^b	1.25	1.18-1.33	<.001	1.26	1.18-1.35	<.001	1.35	1.17-1.56	<.001
ER-status									
positive vs. negative	0.88	0.75-1.04	.14	0.86	0.72-1.03	.11	0.90	0.62-1.32	.60
unknown vs. negative	1.16	0.93-0.43	.19	1.11	0.86-1.43	.43	-	-	-
<i>Model 7</i> PRS₃₁₃^b	1.25	1.18-1.33	<.001	1.26	1.18-1.35	<.001	1.35	1.17-1.56	<.001

PR-status	positive vs. negative	0.95	0.81-1.11	.51	0.92	0.78-1.09	.32	0.91	0.66-1.25	.56
	unknown vs. negative	1.15	0.95-1.40	.14	1.10	0.88-1.37	.40	-	-	-
<i>Model 9</i>										
PRS₃₁₃^b		1.25	1.18-1.33	<.001	1.26	1.17-1.34	<.001	1.34	1.16-1.55	<.001
HER2-status	positive vs. negative	0.84	0.64-1.11	.22	0.76	0.56-1.05	.10	0.70	0.45-1.10	.12
	unknown vs. negative	1.29	1.11-1.50	.001	1.28	1.08-1.52	.004	-	-	-
<i>Model 10</i>										
PRS₃₁₃^b		1.25	1.17-1.32	<.001	1.26	1.17-1.34	<.001	1.35	1.16-1.56	<.001
Chemotherapy	yes vs. no	0.86	0.73-1.01	.06	0.99	0.83-1.19	.92	0.89	0.64-1.25	.51
	unknown vs. no	1.09	0.91-1.31	.34	1.20	0.97-1.47	.09	-	-	-
<i>Model 11</i>										
PRS₃₁₃^b		1.25	1.18-1.33	<.001	1.26	1.18-1.35	<.001	1.36	1.17-1.57	<.001
Endocrine therapy	yes vs. no	0.75	0.64-0.88	.001	0.92	0.75-1.12	.41	0.78	0.55-1.11	.17
	unknown vs. no	0.90	0.75-1.09	.28	1.11	0.87-1.41	.39	-	-	-
<i>Model 12</i>										
PRS₃₁₃^b		1.25	1.17-1.32	<.001	1.26	1.17-1.34	<.001	1.35	1.17-1.56	<.001
Radiotherapy	yes vs. no	1.00	0.85-1.18	1.00	0.98	0.82-1.18	.85	1.35	0.88-2.08	.17
	unknown vs. no	1.41	1.14-1.74	.001	1.18	0.93-1.50	.17	-	-	-
<i>Model 13</i>										
PRS₃₁₃^b		1.25	1.17-1.32	<.001	1.25	1.17-1.34	<.001	1.34	1.16-1.55	<.001
Year of first breast cancer diagnosis		0.95	0.94-0.96	<.001	0.95	0.93-0.96	<.001	0.90	0.86-0.95	<.001
<i>Model 14</i>										
PRS₃₁₃^b	full model ^c	1.23	1.16-1.31	<.001	1.25	1.16-1.33	<.001	1.33	1.15-1.53	<.001

Abbreviations: PRS = polygenic risk score, CBC = contralateral breast cancer, HR = hazard ratio, CI = confidence interval, SD = standard deviation, ER = estrogen receptor, PR = progesterone receptor, HER2 = human epidermal growth factor receptor 2

^a All analyses were performed with attained age as the time scale

^b Coefficients to construct the PRS₃₁₃ are shown in Table S3. The PRS₃₁₃ was standardized by SD=0.61, in line with Mavaddat et al.¹

^c Adjusted for family history, nodal status, tumor size, differentiation grade, morphology, ER status, HER2 status, chemotherapy, endocrine therapy, radiotherapy, and year of first breast cancer diagnosis

Table S7. Five- and ten-year cumulative risks of contralateral breast cancer by the 313-variant PRS (PRS₃₁₃) for different age groups

Age at first breast cancer diagnosis (years)	5-year cumulative CBC risks (%) range by age					10-year cumulative CBC risks (%) range by age				
	5 th percentile PRS ₃₁₃	10 th percentile PRS ₃₁₃	50 th percentile PRS ₃₁₃	90 th percentile PRS ₃₁₃	95 th percentile PRS ₃₁₃	5 th percentile PRS ₃₁₃	10 th percentile PRS ₃₁₃	50 th percentile PRS ₃₁₃	90 th percentile PRS ₃₁₃	95 th percentile PRS ₃₁₃
30-34	1.9-3.3	2.1-3.6	2.8-4.7	3.7-6.2	4.0-6.8	3.3-4.4	3.6-4.8	4.7-6.3	6.2-8.3	6.8-9.1
35-39	0.8-2.2	0.9-2.4	1.2-3.2	1.6-4.2	1.7-4.6	2.2-3.9	2.4-4.2	3.2-5.5	4.2-7.2	4.6-8.0
40-44	1.5-2.9	1.7-3.2	2.2-4.2	2.9-5.5	3.2-6.0	2.9-4.9	3.2-5.3	4.2-7.0	5.5-9.1	6.0-10.0
45-49	1.4-2.5	1.5-2.8	2.0-3.7	2.6-4.8	2.9-5.3	2.5-4.2	2.8-4.5	3.7-6.0	4.8-7.8	5.3-8.6
50-54	1.4-2.9	1.5-3.1	2.0-4.1	2.6-5.5	2.9-6.0	2.9-4.8	3.1-5.3	4.1-6.9	5.5-9.1	6.0-10.0
55-59	1.6-3.3	1.8-3.6	2.4-4.7	3.1-6.2	3.4-6.8	3.3-5.3	3.6-5.7	4.7-7.5	6.2-9.8	6.8-10.8
60-64	1.8-3.5	1.9-3.8	2.6-5.0	3.4-6.5	3.7-7.2	3.5-5.5	3.8-6.0	5.0-7.9	6.5-10.3	7.2-11.3
65-70	1.5-3.5	1.7-3.8	2.2-5.0	2.9-6.6	3.2-7.2	3.5-4.6	3.8-5.0	5.0-6.6	6.6-8.7	7.2-9.5

Abbreviations: PRS = polygenic risk score, CBC = contralateral breast cancer

Coefficients to construct the PRS₃₁₃ are shown in Table S3. The PRS₃₁₃ was standardized by SD=0.61, in line with Mavaddat et al¹. The CBC incidences for each age group were calculated based on incidence data from the Netherlands Cancer Registry² and relative risks estimated as described in the Material and Methods. In contrast to Table 4, death was not taken into account as competing risk

Table S8. Estimates of unilateral- and contralateral breast cancer risk by the 313-variant PRS (PRS₃₁₃) in the European case-case series and the Asian case-case series

	European						Asian		
	Case-case series ^a			Validation set ^b			Case-case series ^a		
PRS ₃₁₃ ^c	OR per unit SD	95%CI	P-value	OR per unit SD	95%CI	P-value	OR per unit SD	95%CI	P-value
Unilateral breast cancer versus control	1.82	1.80-1.84	<.001	1.67	1.59-1.76	<.001	1.56	1.52-1.60	<.001
CBC versus unilateral breast cancer	1.30	1.26-1.35	<.001	1.39	1.13-1.70	.002	1.15	1.02-1.29	.02

Abbreviations: PRS = polygenic risk score, CBC = contralateral breast cancer, OR = odds ratio, SD = standard deviation, CI = confidence interval

^a Adjusted for country and age. For all women with unilateral- and contralateral breast cancer we used age at first breast cancer diagnosis, and for control women without any diagnosis of breast cancer we used age at baseline questionnaire.

^b The validation set was previously used to develop the PRS₃₁₃; see details in materials and methods. For analyses in the current paper, this set is nested within the case-case series. These analyses were additionally adjusted for 10 principal components for comparability with the originally published PRS₃₁₃ overall estimates¹

^c Coefficients to construct the PRS₃₁₃ are shown in Table S3. The PRS₃₁₃ was standardized by SD=0.61, in line with Mavaddat et al.¹

Supplemental Note

Our initial aim was to externally validate our results using the UK Biobank, which seemed the most suitable cohort given the large number of women diagnosed with breast cancer with information available on the PRS₃₁₃. However, when we started the analyses, it turned out that the UK Biobank had no information available on the laterality of the second breast tumor. Therefore, we were unable to distinguish between ipsilateral and contralateral breast cancer, and had to define our endpoint in these analyses as ‘any second breast cancer’. In addition, in comparison to our analyses in the BCAC, we were unable to exclude patients diagnosed with stage IV invasive first breast cancer from the UK Biobank cohort, and had limited information on metastases developed during follow-up.

The association between the overall breast cancer PRS₃₁₃ and (any) second breast cancer was evaluated among women aged ≥ 18 years of European ancestry from the UK Biobank cohort who had had a diagnosis of invasive first breast cancer. UK Biobank samples were genotyped using Affymetrix UK BiLEVE Axiom array and Affymetrix UK Biobank Axiom® array and imputed to the combined 1000 Genome Project v3 and UK10K reference panels using SHAPEIT3 and IMPUTE3⁴. The lowest imputation info score for the variants used in these analyses was 0.86. Samples were included for this analysis of the UK BIOBANK study on the basis of female sex (genetic and self-reported) and ethnicity filter (Europeans/White British ancestry subset). Duplicates and individuals with high degree of relatedness (samples which have >10 putative third degree relatives) were removed, and we randomly excluded one of each related pair first-degree relatives. Samples were also excluded on standard quality control criteria. The PRS₃₁₃ was calculated as a weighted sum of the minor allele dosages; the variant selection and weights are as given by Mavaddat et al¹. The PRS₃₁₃ was standardized by SD=0.61, in line with our BCAC analyses and Mavaddat et al¹.

The final cohort included 10,567 women with invasive breast cancer among whom 302 registry-confirmed second breast cancers developed over 59,260 person-years of follow-up. A Cox proportional hazards model was used to assess the association between PRS_{313} and second breast cancer risk. Time at risk started three months after the age of first breast cancer diagnosis, where this was diagnosed after the baseline questionnaire date, or three months after the baseline questionnaire where first breast cancer was diagnosed before the baseline questionnaire date. Time at risk ended at the age of second breast cancer diagnosis (ipsilateral or contralateral), distant metastasis (where available), death or end of follow-up (at latest December 10, 2016). Potential effect modification of the PRS_{313} by age was evaluated by adding an interaction term ($PRS_{313} \times \text{age at first breast cancer diagnosis [continuous]}$) in the model. We performed a separate analysis for invasive second breast cancer (241 breast cancers), where we censored on in situ second breast cancer.

The HR for a second breast cancer (in situ or invasive) per SD of PRS_{313} in the UK Biobank cohort was 1.13 (95%CI=1.01-1.26). We found no indication for interaction with age at first breast cancer diagnosis ($HR_{\text{interaction}}=1.00$, 95%CI=0.99-1.01; $P=0.87$). When analyses were restricted to invasive second breast cancer, the HR per SD was 1.13 (95%CI=1.00-1.29).

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