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Original Research

Incorporating progesterone receptor expression into the PREDICT breast prognostic model

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Abstract ***Background:*** Predict Breast (www.predict.nhs.uk) is an online prognostication and treatment benefit tool for early invasive breast cancer. The aim of this study was to incorporate the prognostic effect of progesterone receptor (PR) status into a new version of PREDICT and to compare its performance to the current version (2.2).
Method: The prognostic effect of PR status was based on the analysis of data from 45,088 European patients with breast cancer from 49 studies in the Breast Cancer Association Consortium. Cox proportional hazard models were used to estimate the hazard ratio for PR status. Data from a New Zealand study of 11,365 patients with early invasive breast cancer were used for external validation. Model calibration and discrimination were used to test the model performance.
Results: Having a PR-positive tumour was associated with a 23% and 28% lower risk of dying from breast cancer for women with oestrogen receptor (ER)-negative and ER-positive breast cancer, respectively. The area under the ROC curve increased with the addition of PR status from 0.807 to 0.809 for patients with ER-negative tumours ($p = 0.023$) and from 0.898 to 0.902 for patients with ER-positive tumours ($p = 2.3 \times 10^{-6}$) in the New Zealand cohort. Model calibration was modest with 940 observed deaths compared to 1151 predicted.
Conclusion: The inclusion of the prognostic effect of PR status to PREDICT Breast has led to an improvement of model performance and more accurate absolute treatment benefit predictions for individual patients. Further studies should determine whether the baseline hazard function requires recalibration.

1. Introduction

Accurate predictions of individualised survival estimates and benefits of adjuvant therapy following surgery are essential for clinical decision-making for patients with early invasive breast cancer. PREDICT Breast (www.breast.predict.nhs.uk) is an online prognostication and treatment benefit tool to aid clinical decision-making for adjuvant therapy after surgery for patients with early invasive breast cancer [1]. The model uses information about age at diagnosis and tumour characteristics to predict 5-, 10- and 15-year mortality and the benefit of treatment of adjuvant cytotoxic chemotherapy, hormone therapy, trastuzumab and/or bisphosphonate therapy. The clinico-pathological factors used in the current version (v2.2) are tumour size, tumour grade, number of positive lymph nodes, oestrogen receptor (ER) status, human epidermal growth factor receptor 2 (HER2) status, KI67 status and mode of detection [1–3]. PREDICT Breast was developed using cancer registry data from 5694 women diagnosed in East Anglia, United Kingdom, between 1999 and

2003 [4]. Separate breast cancer-specific mortality models were derived for ER-negative tumours and ER-positive tumours. The survival for patients with breast cancer is estimated by the hazard ratios of the risk factors in combination with the baseline survival function derived from a Cox proportional hazards regression model. It is possible to include additional prognostic factors into the model, even if data on those factors were not available in the data used to derive the model, by applying the external estimates of prognostic effects to the baseline hazard function. This approach was used to incorporate HER2 status and KI67 status, which led to an improvement in predictive performance [2,3].

Progesterone receptor (PR) status is a biomarker that has been shown to be prognostic in early invasive breast cancer in a large number of studies [5–11]. It is usually assessed by immunohistochemistry and, in combination with ER status and HER2 status, can be used to classify the breast carcinoma subtype [7]. Furthermore, the expression levels of PR predict clinical outcomes and the beneficial effect of adjuvant hormonal treatments [6,8–10]. Thus, the addition of PR status to the PREDICT Breast model has the potential to improve the discrimination of the model and improve its clinical utility.

We had two specific aims. The first was to obtain estimates of the relative hazard for breast cancer-specific mortality associated with PR status after adjusting for the prognostic factors included in PREDICT Breast v2.2. The second was to incorporate this hazard ratio estimate into the PREDICT Breast model and compare the performance of the new model against the current model (PREDICT Breast version 2.2).

2. Methods

2.1. Prognostic effect of biomarker PR status

We evaluated the prognostic effect of PR status using data on patients with breast cancer of European ancestries collected by 49 studies in the Breast Cancer

Table 1
Patient characteristics for the BCAC studies with European patients with breast cancer (n = 45,088) and the New Zealand validation cohort (n = 11,365).

	BCAC European ancestries		New Zealand cohort	
	N	Mean (sd), unless stated otherwise	N	Mean (sd), unless stated otherwise
Age, years	45,088	57.1 (11.9)	11,365	57.1 (12.2)
Follow-up time, years	45,088	8.1 (5.0)	11,365	5.3 (3.6)
Tumour size, cm	45,088	2.1 (1.5)	11,365	2.3 (1.7)
Tumour grade, n (%)	45,088		11,365	
Grade 1		8776 (19.5)		2841 (25.0)
Grade 2		21,945 (48.7)		5312 (46.7)
Grade 3		14,367 (31.9)		3212 (28.3)
ER/PR status, n(%)	45,088		11,365	
ER−/PR−		7474 (16.6)		2026 (17.8)
ER−/PR+		1187 (2.6)		168 (1.5)
ER+/PR−		6232 (13.8)		1583 (13.9)
ER+/PR+		30,195 (67.0)		7588 (66.8)
HER2 status, n (%)	32,328		9213	
Negative		27,108 (83.9)		7774 (84.4)
Positive		5220 (16.1)		1439 (15.6)
No. of positive lymph nodes	45,088	1.2 (2.7)	11,365	1.7 (3.4)
Mode of detection, n (%)	45,088		11,365	
Clinically detected		21,639 (48.0)		6516 (57.3)
Screen detected		2433 (5.4)		4849 (42.7)
Missing		21,016 (46.6)		
Chemotherapy, n (%)	36,991		11,365	
No		20,157 (54.5)		7391 (65.0)
Yes		16,834 (45.5)		3974 (35.0)
Hormone therapy, n (%)	35,486		11,365	
No		10,724 (30.2)		4340 (38.2)
Yes		24,762 (69.8)		7025 (61.8)
Radiotherapy, n(%)	32,166			
No		8360 (26.0)		
Yes		23,806 (74.0)		
Trastuzumab, n(%)	22,529			
No		20,997 (93.2)		
Yes		1532 (6.8)		
Number of deaths, n(%)	45,081	6974 (15.5)	11,365	1609 (14.2)
Causes of death, n(%)	5925		1609	
Breast cancer		3531 (59.6)		940 (58.2)
Other causes		2394 (40.4)		568 (35.3)
Unknown causes				101 (6.3)

Association Consortium (BCAC) (Supplementary Table S1). All contributing studies were approved by the relevant research ethics committee. Data for women diagnosed with early invasive breast cancer between 1990 and 2017 with complete information on the primary clinico-pathological factors used in the current version of PREDICT v2.2 – tumour size, tumour grade, number of positive lymph nodes, ER status, PR status – were included in the analyses. HER2 status was also available for most patients and could be included as PREDICT allows for missing HER2 data. The mode of detection was missing for 85% of the cases: we assumed that patients aged younger than 50 years or older than 70 years at diagnosis had been clinically detected and mean imputation was used for the remaining missing data. Cases with the following characteristics were excluded: aged younger than 25 or older than 85 at diagnosis, tumour diameter over 20 cm, more than 20 positive lymph nodes. PR status was available for 45,088 patients (13,706 PR-negative tumours and 31,382 PR-positive tumours) (Table 1). Data on ER, HER2 and PR status were collected separately by each study. For some studies, the data were from clinical records – and the definition of positivity may have varied from hospital to hospital. Other studies collected pathology material and carried out immunohistochemistry for these markers as part of the research. Different scoring systems and different definitions of positivity were used by different studies. Vital status and cause of death were obtained from the hospital medical records or the cancer registry or via linkage to death notifications.

We estimated the hazard ratio for PR-positive tumours compared with PR-negative tumours using a Cox proportional hazards model for time to death from breast cancer stratified by study and adjusted for the PREDICT Breast v2.2 prognostic score. The PREDICT Breast v2.2 prognostic score (a log hazard ratio) was calculated for each case according to the formula reported in Candido dos Reis *et al.* (Table 1) [1]. Follow-up time was defined as the time from diagnosis to last follow-up or death from breast cancer or 15 years after diagnosis, whichever came first. In order to account for prevalent cases, time at risk started at the study entry (left truncation). This provides an unbiased estimate of the hazard ratio [12]. Separate models were derived for ER-negative breast cancer cases and ER-positive breast cancer cases.

2.2. Incorporation of PR status into PREDICT breast

The absolute risk of breast cancer-specific mortality is estimated in PREDICT Breast by applying the prognostic score to an estimate of the baseline hazard that was developed using a cohort of breast cancer cases with unknown information on PR status. Thus, the underlying baseline hazard represents breast cancer cases with an average PR status. The estimates of the prognostic effects of PR status for ER-negative tumours and ER-positive tumours were, therefore, rescaled to give an average hazard ratio of unity using a prevalence of PR positivity of 14% in ER-negative cases and 83% in ER-positive tumours.

2.3. Validation study population

Data from a New Zealand population-based cancer registry were used for model validation [13]. Data were available on 11,365 patients with early invasive breast cancer (2194 ER-negative and 9171 ER-positive) diagnosed between 2000 and 2014 after the exclusion of cases with metastasis at diagnosis (639), those younger than 25 or older than 85 years old (524), tumour diameter larger than 20 cm (5), more than 20 positive lymph nodes (232), inconsistent follow-up time information (2) and those that did not undergo primary surgery (938).

Information on adjuvant systemic cancer treatments, chemotherapy and hormone therapy were also recorded. The New Zealand cohort did not include information on

Table 2
Hazard ratios (95% C.I.) for progesterone receptor (PR) status and other prognostic factors for breast cancer-specific mortality stratified by oestrogen receptor (ER) status and study derived from the BCAC data for European ancestries.

	ER-negative	*p*-value	ER-positive	*p*-value
	HR (95% C.I.)		HR (95% C.I.)	
Univariable				
PR+ v PR−	0.65 (0.54–0.80)	2.0×10^{-5}	0.60 (0.55–0.67)	$<10^{-15}$
Multivariable with PREDICT prognostic index[a]				
PR+ v PR−	0.77 (0.64–0.94)	0.009	0.72 (0.65–0.79)	3.7×10^{-11}
Multivariable with individual prognostic factors				
PR+ v PR−	0.76 (0.60–0.98)	0.031	0.69 (0.62–0.78)	1.6×10^{-9}
Age diagnosis (per 5 years)	1.04 (1.00–1.08)	0.028	1.03 (1.00–1.06)	0.030
Size (per cm)	1.17 (1.13–1.22)	$<10^{-15}$	1.13 (1.10–1.16)	$<10^{-15}$
Nodes (per positive node)	1.13 (1.11–1.14)	$<10^{-15}$	1.12 (1.10–1.13)	$<10^{-15}$
Grade				
2 versus 1	2.22 (1.20–4.10)	0.011	2.51 (2.04–3.08)	$<10^{-15}$
3 versus 1	2.52 (1.38–4.62)	2.7×10^{-3}	4.26 (3.44–5.28)	$<10^{-15}$
Screen detected versus clinically detected	0.65 (0.45–0.93)	0.018	0.53 (0.43–0.65)	1.1×10^{-9}
HER2+ v HER2−	0.96 (0.81–1.13)	0.603	1.10 (0.96–1.26)	0.163

[a] PRS coefficient constraint to be one.

specific chemotherapy regimes. To derive the prognostic score, we assumed that patients who underwent chemotherapy before 2010 were treated with anthracycline-based regimen, and for those treated after this time, we assumed a taxane-based regimen. This is based on data for the most commonly used regimen in New Zealand (Mark Elwood personal communication). In addition, information on the use of trastuzumab was not collected during follow-up. We assume that patients with a positive HER2 tumour and that were diagnosed after 2010, underwent trastuzumab treatment.

The dates and causes of death were extracted from the hospital records and from mortality records until 31st December 2014 and all patients were censored after this date. The primary end-point was breast cancer-specific survival. The expected survival probability for each patient was based on a follow-up time that was different for each patient up to a maximum of 15 years. For patients who survived, follow-up was from the date of diagnosis until the date of last follow-up. For patients who died, potential follow-up time was calculated as if the patient had survived to the end of the study, which is from the date of diagnosis until 31st December 2014.

For each patient, their breast cancer risk predictions were estimated using the two models; PREDICT version 2.2 and PREDICT version 2.2 with the inclusion of PR status (v2.3). Model calibration was performed to investigate the accuracy of the mortality estimates predicted by each model compared to the observed mortality rate. Additionally, a Chi-square test was used as a goodness-of-fit test in which the observed events were also compared with the number of predicted events (1 d.f.). Model discrimination was also evaluated through the calculation of the AUC (area under the receiver–operator–characteristic curve) for up to 15-year breast cancer mortality. The AUC was used to measure the accuracy of the classification of cases and non-cases for the two prediction models and to test for any beneficial effect of the addition of PR status to PREDICT Breast. The comparison of AUCs was done using the method of De Long *et al.* [14] implemented in the R package *pROC*. All analyses were conducted using R v4.1.2 in the R Studio environment.

3. Results

The 49 BCAC studies included 45,088 eligible European patients of whom 13,706 (30%) had PR-negative tumours and 31,382 (70%) had PR-positive tumours (Table 1). During follow-up, there were 6974 recorded deaths with approximately 11 breast cancer deaths per 1000 person-years. The patient characteristics of the New Zealand cohort were very similar to those in the studies of BCAC apart from the proportion of patients that underwent chemotherapy (35%), which was lower than that for BCAC (46%).

Initial analyses were restricted to patients of European ancestries. In univariate analyses, PR expression was associated with a better prognosis, with the magnitude of the effect being greater in ER-positive disease (Table 2). The effect of PR expression was attenuated after adjusting for other prognostic factors. We evaluated whether the effect of PR varied by age or HER2 status by including an interaction term in the multi-variable model. There was little evidence for the interaction in either age at diagnosis ($p = 0.65$ in ER-positive and $p = 0.43$ in ER-negative) or HER2 status ($p = 0.36$ in ER-positive and $p = 0.91$ in ER-negative).

We also assessed between-study heterogeneity and plotted the estimated beta coefficient of PR status per study adjusted for the prognostic index (Supplementary Fig. S1). There was no evidence of heterogeneity in the ER-negative model ($p = 0.99$) or in the ER-positive model ($p = 0.26$).

The visual examination of plots of log-cumulative hazard against log-time and the Schoenfeld residuals against time showed that there was no serious violation of the proportional hazards assumption (Supplementary Figs. S2 and S3). The hazard ratios for the other prognostic factors from the multivariable model that included each prognostic factor separately were slightly different to those in the PREDICT model. Of particular note is that in the BCAC dataset, a significant association was observed for the mode of detection in ER-negative disease. It has previously been reported to be associated only in ER-positive tumours.

In order to apply the PR hazard ratio to the PREDICT Breast baseline hazard, it needed to be rescaled such that the mean hazard ratio was unity with the purpose that the reference category for the hazard ratio is a hypothetical case with average PR status. The proportion of cases that are PR-positive used for rescaling was the average from the combined BCAC studies (14% for ER-negative and 83% for ER-positive cases). The rescaled hazard ratios were 1.03 for PR-negative/ER-negative, 0.80 for PR-positive/ER-negative, 1.30 for PR-negative/ER-positive and 0.94 for PR-positive/ER-positive. The hazard ratios for all the other prognostic

Table 3
The discrimination for up to 15-year breast cancer-specific mortality in the New Zealand validation cohort.

	C-index without PR status	C-index with PR status	*p*-value
ER specific			
ER-negative	0.807	0.809	0.023
ER-positive	0.898	0.902	2.3×10^{-6}
Ethnicity			
Māori	0.901	0.901	0.983
Pacific	0.897	0.898	0.883
European	0.878	0.881	1.0×10^{-6}
Other ethnicity	0.919	0.923	0.022
Overall	0.885	0.888	1.5×10^{-7}

variables and the baseline hazard function remained unchanged from PREDICT Breast v2.2.

The performance of PREDICT Breast v2.2 with the addition of PR status was then evaluated in the independent New Zealand data set and compared with v2.2. The discrimination for up to 15-year breast cancer-specific mortality of PREDICT as measured by the AUC increased from 0.807 to 0.809 ($p = 0.023$) for patients with ER-negative breast cancer and from 0.898 to 0.902 ($p = 2.3 \times 10^{-6}$) for ER-positive cases (Table 3). The calibration of the model was modest, with 1151 breast cancer deaths predicted compared to 940 that were observed during a 15-year follow-up (goodness-of-fit Chi-squared test $p = 5.0 \times 10^{-10}$) (Table 4). Over-estimation was worse in European patients with ER-negative tumours (366 predicted compared with 281 observed, $p = 8.9 \times 10^{-6}$) than European patients with ER-positive tumours (442 predicted compared to 414 observed, $p = 0.183$). Across ethnicities, the model performs better in ER-positive cases in comparison to ER-negative cases. Fig. 1 shows the calibration of PREDICT Breast including PR status across the quintiles of predicted risk.

The number of observed and predicted deaths from other causes and deaths from all causes in the New Zealand cohort are shown in Tables 5 and 6. Overall, PREDICT Breast with the inclusion of PR status shows to be well-calibrated in predicting non-breast-cancer-specific mortality with an over-estimation of 0.4% (670 predicted compared with 667 observed, $p = 0.908$). The model shows to be slightly over-estimating the number of non-breast cancer deaths in patients of European descent by 6.8% (546 predicted compared with 511 observed,

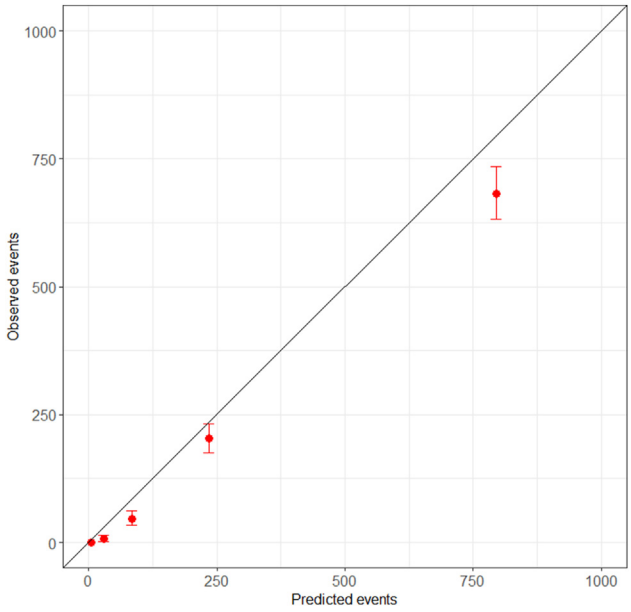

Fig. 1. Calibration plot of observed outcomes at 15 years after diagnosis with 95% confidence intervals against 15-year predicted outcomes at by quintiles of the predicted value in the New Zealand cohort.

Table 4
Cumulative observed versus predicted breast cancer deaths at up to 15 years follow-up by ethnicity in the New Zealand cohort.

	Total number of breast cancer patients by ethnic group	Predicted breast cancer-specific mortality		Observed breast cancer-specific mortality
		Without PR status	With PR status	
Number of deaths				
Māori	1054	117	117	108
Pacific	666	90	90	70
European	8220	799	808	695
Other	1257	121	122	66
Missing	168	14	14	1
Total	11,365	1141	1151	940
ER specific				
ER−				
Māori	177	52	52	44
Pacific	153	43	44	31
European	1576	363	366	281
Other	258	58	58	35
Missing	30	7	8	1
Total	2194	523	528	392
ER+				
Māori	877	65	65	64
Pacific	513	47	46	39
European	6644	436	442	414
Other	999	63	64	31
Missing	138	6	6	0
Total	9171	617	623	548

Table 5
Cumulative observed versus predicted other-cause/non-breast cancer deaths at up to 15 years follow-up by ethnicity in the New Zealand cohort.

	Total number of breast cancer patients by ethnic group	Other-cause/non-breast cancer-specific mortality		Observed other-cause mortality
		Without PR status	With PR status	
Number of deaths				
Māori	1054	40	40	88
Pacific	666	27	28	32
European	8220	547	546	511
Other	1257	47	47	36
Missing	168	9	9	0
Total	11,365	671	670	667
ER specific				
ER−				
Māori	177	7	7	16
Pacific	153	6	6	6
European	1576	101	101	100
Other	258	9	9	8
Missing	30	2	2	0
Total	2194	125	125	130
ER+				
Māori	877	34	34	72
Pacific	513	21	21	26
European	6644	446	446	411
Other	999	38	38	28
Missing	138	7	7	0
Total	9171	546	546	537

Table 6
Cumulative observed versus predicted all-cause deaths at up to 15 years follow-up by ethnicity in the New Zealand cohort.

	Total number of breast cancer patients by ethnic group	All-cause mortality		Observed all-cause mortality
		Without PR status	With PR status	
Number of deaths				
Māori	1054	157	157	196
Pacific	666	118	118	102
European	8220	1346	1355	1206
Other	1257	168	169	102
Missing	168	23	23	1
Total	11,365	1811	1821	1607
ER specific				
ER−				
Māori	177	59	59	60
Pacific	153	50	50	37
European	1576	464	467	381
Other	258	67	67	43
Missing	30	9	9	1
Total	2194	648	652	522
ER+				
Māori	877	98	98	136
Pacific	513	68	67	65
European	6644	882	888	825
Other	999	101	102	59
Missing	138	14	13	0
Total	9171	1163	1169	1085

$p = 0.134$), whilst in patients from Pacific origin they are slightly under-estimated (28 predicted compared with 32 observed, $p = 0.450$). While the model performs better in these ethnic groups, it performs worse in Māori patients (40 predicted compared with 88 observed, $p = 3.2 \times 10^{-14}$). Both models (PREDICT Breast versus PREDICT Breast including PR status) show to over-estimate the all-cause mortality by approximately 13%, regardless of ER status. Similar to the other-cause mortality results, the models show to over-estimate the number of predicted all-cause deaths in most ethnic groups. However, there is an under-estimation of all-cause deaths in patients of Māori descent.

We then carried out a sensitivity analysis using the alternative assumptions for chemotherapy and trastuzumab treatment. Table S2 shows the predicted breast cancer deaths with the assumption that patients who underwent chemotherapy were treated with anthracycline-based regimen (second-generation regimen). Table S3 shows the predicted breast cancer deaths with the assumptions that all patients with HER2-positive tumours were treated with trastuzumab, and patients who underwent chemotherapy and were diagnosed before 2010 were treated with anthracycline-based regimen and for those diagnosed after this time were treated with a taxane-based regimen. The model appears to be miscalibrated and results show that the calibration is sensitive to the treatment assumptions made prior to the analyses.

In order to determine the clinical impact of the small improvement in discrimination, we estimated the reclassification of risk for PREDICT v2.2 + PR compared to PREDICT v 2.2 based on classifying cases from the New Zealand cohort into three categories of breast cancer-specific mortality at ten years, less than 15%, 15% to less than 20% and 20% or greater. These thresholds are approximately equivalent to the thresholds for the absolute risk reduction of chemotherapy of 3% and 5% used by the Cambridge Breast Unit Multidisciplinary Team for clinical decision-making [15]. Table 7 shows that in total 4.2% of cases changed risk category, of which 2.4% changed from a lower risk category to a higher risk category.

4. Discussion

The primary aim of this study was to estimate the prognostic effect – as the relative hazard – of PR expression in breast cancer after adjusting for the other prognostic factors incorporated in the PREDICT Breast prognostic tool. Importantly, the effects of other prognostic factors were constrained to the same effect sizes as used in the PREDICT Breast model. This enabled us to incorporate progesterone expression into PREDICT Breast by applying the relative hazard to the baseline hazard which is specified in the PREDICT Breast model. The BCAC data set on which this analysis was based is large, with over 45,000 cases of European ancestries from 49 separate studies from around the world and over 3500 deaths from breast cancer during follow-up. In addition to the large sample size, the heterogeneity inherent in combining data from multiple studies is strength as the findings should be robust and widely generalisable. While a large number of cases of south Asian ancestries were also available from the BCAC data set, there were a small number of breast cancer deaths during the follow-up and impact of ancestry on the association between PR expression and prognosis could not be reliably assessed.

The heterogeneity of study design and conduct is also reflected in the measurement of the prognostic factors included in the analyses. In particular, different studies used different data sources to determine ER, HER2 and PR status including clinical records and research data. Consequently, different studies used slightly different definitions to classify ER, HER2 and PR status and

Table 7
Reclassification of predicted breast cancer-specific mortality following the inclusion of PR status into PREDICT Breast.

	Predicted breast cancer-specific mortality	PREDICT Breast (including PR status)		
		[0.00–0.15)	[0.15–0.20)	[0.20–1.00]
PREDICT Breast	**[0.00–0.15)**	7191 (63.3%)	137 (1.2%)	0 (0%)
	[0.15–0.20)	115 (1.0%)	859 (7.6%)	138 (1.2%)
	[0.20–1.00]	0 (0%)	92 (0.8%)	2833 (24.9%)

these data could not be fully harmonised across studies. Any measurement error resulting from this is likely to have biased the association of PR status with survival towards the null but any such bias is expected to be small.

Our results are broadly similar to the extensive published data [5–11,16,17] and show that patients with a positive PR tumour have a better survival than patients with a PR-negative tumour regardless of their ER status. There was little difference in the relative hazard estimates after adjusting for a prognostic index constrained to the effect size used in the PREDICT Breast model or in full, multi-variable model that allowed the hazard ratios for the other prognostic factors to fit the data. Previous reports have shown that the prognostic effect of PR status varies with age at diagnosis with a bigger effect being observed in younger patients [16,17], particularly during the first five years of follow in one of the studies [16]. However, we found little evidence for a difference in the effect with age.

We used the relative hazard estimates to incorporate progesterone receptor expression into the PREDICT Breast model and compared the performance of the modified model with that of the current version of PREDICT Breast as used in the online web tool (v2.2). This was done using a completely independent data set from New Zealand. The addition of a single prognostic factor to a multi-variable prediction model would not be expected to improve the performance of the model substantially. Nevertheless, the addition of PR status resulted in a small, but statistically significant improvement in the discrimination of PREDICT Breast compared with the current version. Similarly, the small proportion of patients being reclassified when using clinically relevant categories of risk that was observed was as would be expected. The calibration of the modified version of PREDICT Breast would not be expected to change much as calibration is primarily dependent on the baseline hazard which was the same in the modified and current models and then depends on the assumption about the proportion of cases that are PR-positive used to rescale the hazard ratios as described in the methods. The calibration of the modified models in an independent data set was modest with the number of breast cancer deaths in the New Zealand cohort being over-estimated by 22%. This was, as expected, similar – albeit slightly worse – to the calibration of the current model. The miscalibration was similar for all ancestries and was worse in patients with ER-negative. PREDICT Breast has previously been shown to be well-calibrated in cases series from the UK, Canada, the Netherlands and Malaysia, and the reasons for the poorer performance in the New Zealand data set are not clear. One possible explanation is that the baseline hazard for PREDICT is based on a cohort of patients from the UK diagnosed from 1999 to 2004 whereas the New Zealand cohort was diagnosed from 2000 to 2014. There have been improvements in prognosis over time and so some over-estimation of deaths is expected. This is supported by the observation that there is an improvement in the calibration of PREDICT Breast including PR status when performing analysis on patients diagnosed between 2000 and 2004, with an over-estimation in breast cancer deaths of 7.7% in all patients and 3.6% in European patients, compared to 22.4% and 16.3% for patients diagnosed between 2000 and 2014. Some of these improvements are the result of the introduction of newer therapies such as bisphosphonates, increased the duration of hormone therapies and improvements in the management of disease at the time of relapse. However, information on these therapies was not available for the validation data and so could not be accounted for in the analyses. A simple country-specific recalibration of the baseline hazard function or a re-estimation of the baseline hazard using more contemporaneous data would improve the model performance.

The expression of biomarkers such as ER, HER2 and PR is continuous but then dichotomised based on a threshold for use in clinical practice. For ER and HER2 status, this is primarily done to facilitate decision-making for specific adjuvant therapies. There is good evidence that the prognostic effect of these biomarkers varies with the level of expression [18–20] and the inclusion of a multi-category ordinal scale or a continuous measure of expression in the model has the potential to improve model performance.

In conclusion, the incorporation of the prognostic effect of PR status into PREDICT Breast has resulted in a small, statistically significant improvement in discrimination with some reclassification in clinically relevant risk thresholds. On the other hand, the calibration of the modified PREDICT model in an independent data set was slightly poorer. The improvement in discrimination is likely to be generalisable across diverse case cohorts as it is primarily dependent on the magnitude of the hazard ratio associated with progesterone receptor status which is likely to be robustly estimated. In contrast, calibration is dependent on the baseline hazard which may vary across different populations and time periods as well as the distribution of the biomarker in different populations. Thus, progesterone receptor expression will be included into a new version of PREDICT Breast (v2.3) based on the improvement in discrimination and the reclassification. Further studies should investigate the potential improvement that recalibrating the baseline hazard function could have on country-specific model performance.

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Isabelle Grootes: formal analysis, methodology, software, validation, writing – original draft, writing – review & editing, visualisation.

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Conflict of interest statement

None declared.

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Appendix A. Supplementary data

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