

## Research article

## Open Access

**The androgen receptor CAG repeat polymorphism and modification of breast cancer risk in *BRCA1* and *BRCA2* mutation carriers**

Amanda B Spurdle<sup>1</sup>, Antonis C Antoniou<sup>2</sup>, David L Duffy<sup>1</sup>, Nirmala Pandeya<sup>1</sup>, Livia Kelemen<sup>1</sup>, Xiaoqing Chen<sup>1</sup>, Susan Peock<sup>2</sup>, Margaret R Cook<sup>2</sup>, Paula L Smith<sup>2</sup>, David M Purdie<sup>1</sup>, Beth Newman<sup>3</sup>, Gillian S Dite<sup>4</sup>, Carmel Apicella<sup>4</sup>, Melissa C Southey<sup>4</sup>, Graham G Giles<sup>5</sup>, John L Hopper<sup>4</sup>, kConFaB, EMBRACE Study Collaborators, ABCFS, AJBCS, Georgia Chenevix-Trench<sup>1</sup> and Douglas F Easton<sup>2</sup>

<sup>1</sup>Queensland Institute of Medical Research, Brisbane, Australia

<sup>2</sup>Cancer Research UK Genetic Epidemiology Unit, University of Cambridge, Cambridge, UK

<sup>3</sup>School of Public Health, Queensland University of Technology, Brisbane, Australia

<sup>4</sup>University of Melbourne, Melbourne, Australia

<sup>5</sup>The Cancer Council Victoria, Carlton, Australia

Corresponding author: Amanda B Spurdle, [mandyS@qimr.edu.au](mailto:mandyS@qimr.edu.au)

Received: 24 Jun 2004 Revisions requested: 29 Jul 2004 Revisions received: 5 Oct 2004 Accepted: 11 Nov 2004 Published: 16 Dec 2004

*Breast Cancer Res* 2005, **7**:R176-R183 (DOI 10.1186/bcr971)

© 2004 Spurdle *et al.*, licensee BioMed Central Ltd.

This is an Open Access article distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/2.0>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is cited.

**Abstract**

**Introduction** The androgen receptor (*AR*) gene exon 1 CAG repeat polymorphism encodes a string of 9–32 glutamines. Women with germline *BRCA1* mutations who carry at least one *AR* allele with 28 or more repeats have been reported to have an earlier age at onset of breast cancer.

**Methods** A total of 604 living female Australian and British *BRCA1* and/or *BRCA2* mutation carriers from 376 families were genotyped for the *AR* CAG repeat polymorphism. The association between *AR* genotype and disease risk was assessed using Cox regression. *AR* genotype was analyzed as a dichotomous covariate using cut-points previously reported to be associated with increased risk among *BRCA1* mutation

carriers, and as a continuous variable considering smaller allele, larger allele and average allele size.

**Results** There was no evidence that the *AR* CAG repeat polymorphism modified disease risk in the 376 *BRCA1* or 219 *BRCA2* mutation carriers screened successfully. The rate ratio associated with possession of at least one allele with 28 or more CAG repeats was 0.74 (95% confidence interval 0.42–1.29;  $P = 0.3$ ) for *BRCA1* carriers, and 1.12 (95% confidence interval 0.55–2.25;  $P = 0.8$ ) for *BRCA2* carriers.

**Conclusion** The *AR* exon 1 CAG repeat polymorphism does not appear to have an effect on breast cancer risk in *BRCA1* or *BRCA2* mutation carriers.

**Keywords:** *AR*, *BRCA1*, *BRCA2*, modifier

**Introduction**

A CAG length polymorphism within exon 1 of the androgen receptor (*AR*) gene encodes a string of 9–32 glutamines. Even within this normal range, CAG repeat number is inversely associated with AR-mediated transcriptional activation *in vitro* [1,2]. Involvement of the AR in breast tumorigenesis is suggested by the existence of inactivating germline mutations in the hormone-binding domain in male breast cancer patients [3,4], and by splice variants that dis-

rupt the transactivation domain in female breast tumours and tumour cell lines [5].

There is evidence that suggests an association between longer *AR* CAG repeat length – representative of less active AR – and breast cancer risk at the population level (for review, see Lillie and coworkers [6]). Using slightly variable definitions of shorter and longer allele size across studies, one study reported a significant twofold increased

risk for breast cancer, another three studies reported a slightly increased risk for breast cancer (1.2- to 1.4-fold), and another reported a 1.7-fold increased risk limited to individuals with a first-degree family history of breast cancer [6].

Several studies have been undertaken to assess the role of the CAG repeat polymorphism as a modifier of breast cancer risk in *BRCA1* and *BRCA2* mutation carriers. The hypothesis-generating study [7] examined *AR* CAG length in 304 female *BRCA1* mutation carriers (54% with breast cancer), and assessed breast cancer risk associated with CAG length as a continuous variable, and at a number of different cut-points. That study reported a 1.8-fold relative risk (95% confidence interval [CI] 1.1–3.1;  $P = 0.03$ ) among the small subgroup of women with at least one *AR* allele of 28 or more CAG repeats in length, with relative risks of 2.6 (95% CI 1.5–4.7;  $P < 0.001$ ) and 4.5 (95% CI 1.3–15.2;  $P = 0.02$ ) for the cut-points  $\geq 29$  CAG repeats and  $\geq 30$  CAG repeats, respectively. Subsequent studies have reported conflicting results. A relative risk of 1.1 (95% CI 0.5–2.6) was observed for women with 28 or more CAG repeats from a pooled analysis of 188 *BRCA1* and *BRCA2* mutation carriers [8], whereas a study of 227 *BRCA1* and *BRCA2* mutation carriers reported shorter mean CAG repeat number in women with breast cancer diagnosed before age 42 years as compared with those diagnosed after this age [9].

It has been hypothesized that *AR* alleles with decreased transactivation might act directly to result in decreased breast cell proliferation, or possibly indirectly via an endocrine or paracrine mechanism whereby altered levels of circulating or stromal hormones might affect mammary epithelial growth [7]. Subsequent biochemical studies reported a protein–protein interaction between the *AR* protein and particular regions of both the *BRCA2* and *BRCA1* proteins. *BRCA2* has been reported to enhance androgen-dependent *AR* activity [10]. Although that study also reported that an expressed truncated *BRCA2* protein encoded by the *BRCA2* L1042X mutation failed to enhance *AR* transactivation [10], it did not examine the effect of *BRCA2* mutation position in general, or which domains of *BRCA2* are required for the *BRCA2*–*AR* interaction.

*BRCA1* has also been reported to enhance androgen-dependent *AR* transactivation [11,12]. Mammalian two-hybrid assays have shown that *BRCA1* amino acids 231–1314 and 1560–1863 are responsible for this direct interaction, with *BRCA1* region 758–1064 observed to bind specifically to the *AR* amino-terminal domain containing the glutamine repeat [11]. Androgen response assays indicated that, although *BRCA1* mutations across the gene all reduce *AR* activity enhancement as compared with the

wild-type, the effect was more marked for mutations up to amino acid 1365 [11]. This was particularly true for a mutation that caused truncation at amino acid 772 within the *BRCA1*–*AR* amino-terminus interaction domain, which had 20% activity relative to the wild-type *BRCA1*. The effect of the *AR* CAG repeat length on *BRCA1*–*AR* interactions has not yet been investigated. However, molecular studies provide some support for a biochemical interaction between *AR* CAG repeat length and *BRCA1* mutation status, in that the decreased *AR* transactivation observed *in vitro* with increasing glutamine length was only observed in the absence of coexpressed *BRCA1* [12].

These data suggest that an association of *AR* CAG repeat length with increased breast cancer risk may be found only in *BRCA1* or *BRCA2* mutation carriers (and not individual germline without *BRCA1* or *BRCA2* mutations), and that *AR*-dependent modification of cancer risk in *BRCA1* and *BRCA2* mutation carriers may differ according to which gene is mutated, and the mutation position relative to *AR*-binding site. To evaluate further the evidence for an association between *AR* CAG repeat length and breast cancer risk in *BRCA1* and *BRCA2* mutation carriers, we genotyped the polymorphism in a large series of female mutation carriers.

## Methods

### Subjects

The distribution of samples according to source, gene and cancer status is shown in Table 1.

A total of 604 living female Australian and British carriers of pathogenic *BRCA1* or *BRCA2* mutations were identified in 376 families from the following sources: the Epidemiological study of *BRCA1* and *BRCA2* Mutation Carriers (EMBRACE; <http://www.srl.cam.ac.uk/genepi/embraceindex.htm>), the Kathleen Cuninghame Consortium for Research into Familial Breast Cancer (kConFab; <http://www.kconfab.org>), the Australian Jewish Breast Cancer Study (AJBCS) [13], and the Australian Breast Cancer Family Study (ABCFS) [14,15]. EMBRACE recruits participants from among women and men referred for genetic testing at clinical genetics centres in the UK and Eire. kConFab recruits participants from multiple-case breast and ovarian cancer families referred for genetic testing at family cancer clinics in Australia and New Zealand. AJBCS recruits Ashkenazi Jewish women reporting a personal or family history of breast or ovarian cancer in a first- or second-degree relative, and living in Melbourne or Sydney, Australia. Finally, ABCFS is a population-based case–control-family study that includes women with a first primary breast cancer recruited through the Victorian and New South Wales cancer registries, and their affected and unaffected relatives. Apart from index cases recruited through

**Table 1****Characteristics of study subjects**

Sample sources	<i>BRCA1</i>		<i>BRCA2</i>		<i>BRCA1</i> and <i>BRCA2</i> <sup>a</sup>
	<i>n</i>	(% of total)	<i>n</i>	(% of total)	<i>n</i>
EMBRACE	247	(64)	92	(42)	0
kConFaB	96	(25)	84	(38)	0
AJBCS	19	(5)	22	(10)	0
ABCFS	20	(5)	23	(10)	1
<b>Total</b>	<b>382</b>		<b>221</b>		<b>1</b>
Affected breast cancer <sup>b</sup>	205	(54)	125	(57)	1
Affected ovarian cancer <sup>b</sup>	24	(6)	8	(4)	0
Number of families	257		118		1

Questionnaire information on potential confounders was available for 344 *BRCA1* carriers (239 EMBRACE, 80 kConFaB, 10 AJBCS and 15 ABCFS) and 200 *BRCA2* carriers (92 EMBRACE, 76 kConFaB, 12 AJBCS, and 20 ABCFS). <sup>a</sup>One individual was found to carry a deleterious mutation in both *BRCA1* and *BRCA2* [19]. <sup>b</sup>Cancer type refers to first primary cancer diagnosis. One *BRCA2* carrier with breast cancer was censored as unaffected at age of prior mastectomy. ABCFS, Australian Breast Cancer Family Study; AJBCS, Australian Jewish Breast Cancer study; EMBRACE, Evaluation of Mutant BRCA Carrier Epidemiology study; kConFaB, Kathleen Cuninghame Consortium for Research into Familial Breast Cancer.

cancer registries for the ABCFS, the cancer status of participants was based on self-report.

For samples recruited through EMBRACE, a pathogenic mutation was defined as an established disease-causing mutation under the classification scheme used by Breast Cancer Information Core <http://research.nhgri.nih.gov/bic/>. For samples recruited through kConFaB, AJBCS and ABCFS, mutations were classified as pathogenic according to the criteria established by kConFab <http://www.kconfab.org/progress/classification.asp>. Specifically, the criteria specify the following as being pathogenic: all truncating mutations, unless there is clear evidence that the mutation is a single nucleotide polymorphism (e.g. terminal *BRCA2* variant); and any variant that is well characterized in family studies of multiple generations, and not found in control individuals, that results in a nonconservative amino acid substitution, and occurs in a residue conserved across species and in a functional domain. All mutations included in the study that were shared across sites were classified as pathogenic according to both routes of definition.

Within Australia, ethical approvals were obtained from the ethics committees of the Peter MacCallum Cancer Institute, The Prince of Wales Hospital, The University of Melbourne, The Cancer Council New South Wales, The Cancer Council Victoria and the Queensland Institute of Medical Research. Ethical approval for the EMBRACE study was obtained from the Eastern Multicentre Research Ethics Committee and the relevant local ethics committees.

Written informed consent was obtained from each participant.

**Molecular methods**

The *AR* exon 1 CAG repeat length was measured by fluorescent polymerase chain reaction PAGE methodology, using the ABI Prism 373 Genescan (Applied Biosystems, Foster City, CA, USA) and Genotyper systems (Applied Biosystems). Details of this method were previously reported [16]. Genotyping was successful for 375 out of 382 (98%) *BRCA1* carriers, 218 out of 221 (99%) *BRCA2* carriers, and the single carrier of both a *BRCA1* and a *BRCA2* mutation.

**Statistical methods**

Individuals with a first diagnosis of primary invasive breast cancer were considered to be affected, whereas individuals with no reported breast or ovarian cancer were censored at age at interview. Individuals with a first diagnosis of primary ovarian cancer were censored as unaffected at age at onset of ovarian cancer, and selected analyses were also performed in which individuals with a first primary diagnosis of ovarian cancer were excluded. All individuals were censored at age of prophylactic mastectomy. Individuals reporting prophylactic surgery included a single *BRCA2* carrier who was subsequently diagnosed with multiple breast cancers 4 and 5 years after surgery, and an additional 12 unaffected individuals (7 *BRCA1* and 5 *BRCA2* carriers) with surgery 1–11 years before interview (average 3 years). Prophylactic oophorectomy of affected and

unaffected individuals was controlled for by adjustment as a time-dependent covariate, as described below.

Linear regression was used to assess the association of *AR* CAG repeat length (smaller allele size, larger allele size and average allele size) with potential confounders within the subset of 364 *BRCA1* carriers and 209 *BRCA2* carriers for whom information was available. The potential confounders included year of birth (categorized into subgroups 1910–1949, 1950–1959 and 1960–1979), age at menarche (categorized as  $\leq 11$ , 11.5–12, 12.5–13, 13.5–14 or  $\geq 14.5$  years), oral contraceptive pill use (ever/never) and parity (categorized as 0 or  $\geq 1$  live births before censored age). Questionnaire information was available from participants on age at first and last live birth, but not age at each live birth. Hence, it was not possible to assess association with parity as an absolute number of live births before censored age, but rather only as a never/ever variable. Associations were assessed separately for affected and unaffected women.

The primary analyses of association between *AR* genotype and disease risk were performed using Cox regression with time to breast cancer onset as the end-point. *AR* CAG repeat length was defined as follows: a binary variable, defined by cut-points investigated in the hypothesis-generating study conducted by Rebbeck and coworkers [7] (namely one or more allele of  $\geq 28$  CAG repeats,  $\geq 29$  CAG repeats, or  $\geq 30$  CAG repeats); or a continuous variable, using the length of the smaller of the two alleles (*AR* small CAG), the larger of the two alleles (*AR* large CAG), and the average length of a participant's two alleles (*AR* average CAG). Rate ratios (RRs) and 95% CIs were estimated with adjustment for source group (as indicated in Table 1) and ethnicity (non-Jewish Caucasian, Jewish, other). Analyses were complicated by the fact that more than one mutation carrier could come from the same family and could not therefore be considered independent. Standard Cox regression provides unbiased RR estimates but their standard errors and CIs are incorrect. This was rectified by computing the confidence limits for the RRs using Huber's sandwich estimator of the covariance matrix [17]. This allows for variation between carriers from the same family without modelling their dependence explicitly. Further analyses adjusted for oophorectomy and parity as time-dependent covariates, and for age at menarche, oral contraceptive pill use and year of birth. Oophorectomy before censored age at interview or diagnosis of breast cancer was reported by 39 *BRCA1* carriers (10 with primary breast cancer) and 21 *BRCA2* carriers (9 with primary breast cancer) with genotype information available.

RRs were estimated separately for *BRCA1* and *BRCA2* carriers, including in both analyses the single individual with a mutation in both genes. Models adjusting for only group

and ethnicity included all individuals with genotype information, namely 376 *BRCA1* carriers (with 200 events) and 219 *BRCA2* carriers (with 122 events). The sample size for *BRCA1* carriers with a putative risk allele was 28 (14 events) for the  $\geq 28$  CAG cut-point, 26 (13 events) for the  $\geq 29$  CAG cut-point, and 11 (4 events) for the  $\geq 30$  CAG cut-point. Similarly, for *BRCA2* carriers it was 17 (10 events) for the  $\geq 28$  CAG cut-point, 14 (7 events) for the  $\geq 29$  CAG cutpoint, and 11 (5 events) for the  $\geq 30$  CAG cut-point. Full models adjusting for year of birth and additional hormonal variables included the 364 *BRCA1* and 219 *BRCA2* carriers with full information on potential confounders, comprising 193 and 116 events, respectively.

In addition, analyses were carried out separately for subgroups of *BRCA1* and *BRCA2* carriers defined by mutation position in relation to proposed AR-binding domains, and/or *in vitro* data regarding mutation effect on AR transactivation [10,11]. For *BRCA1*, subgroups were defined by the mutation position either relative to amino acid 1365 ( $<$  or  $\geq$  nucleotide 4213), because mutations 5' of amino acid 1365 have been shown to have a markedly decreased effect on AR transactivation [11]. This created subgroups including 314 and 62 individuals. In addition, *BRCA1* subgroups were defined by mutation relative to amino acid 1065 ( $<$  or  $\geq$  nucleotide 3311), because this defines the 3' end of the *BRCA1* fragment shown *in vitro* to bind the *AR* amino-terminal domain containing the CAG-encoded polyglutamine tract [11], creating subgroups of 210 and 166 individuals. *BRCA2* subgroups were defined by mutation relative to amino acid 1042 ( $<$  or  $\geq$  nucleotide 3352), because it has been shown that the *BRCA2* L1042X mutation does not enhance AR transactivation [10]. Subgroup sample sizes were 42 and 177. For both *BRCA1* and *BRCA2* subgroup analyses, the 3' and 5' subgroups were termed domain 1 and domain 2, respectively. Protein truncating and splice mutations were stratified into domain 1 or domain 2 according to their nucleotide/amino acid position, whereas all missense mutations were included in domain 2 because these nontruncating mutations may act in a dominant-negative manner.

Although the primary analysis provides a valid test of the association between a genotype and disease risk, it may not provide a consistent estimate of the RR because the disease status of the individuals may have affected the likelihood of ascertainment (for the non-population-based studies). Oversampling of affected individuals is likely, as is presentation of affected carriers at later mean age than unaffected carriers. To correct for this potential bias, we also conducted secondary analyses using the weighted Cox regression approach as described by Antoniou and coworkers (unpublished data), in which individuals are weighted such that the observed breast cancer incidence rates in the study sample are consistent with established

breast cancer risk estimates for *BRCA1* and *BRCA2* mutation carriers. Antoniou and coworkers (unpublished data) have shown that this approach gives estimates that are close to unbiased, but with some loss of power as compared with the standard unweighted approach. Weights were computed separately for *BRCA1* and *BRCA2* mutation carriers using the breast cancer incidence rate estimates reported in the meta-analysis conducted by Antoniou *et al.* [18]. A global set of weights was computed because the number of mutation carriers by study was too small to compute reliable study-specific weights. Moreover, Antoniou *et al.* [18] found no significant differences in the *BRCA1* and *BRCA2* cancer risks by country or study centre. As for unweighted analyses, confidence limits for the risk ratio were calculated using a robust variance approach to allow for the dependence among individuals.

We evaluated the power of detecting the effects reported by Rebbeck and coworkers [7] in our samples of *BRCA1* and *BRCA2* mutation carriers using simulations. For this purpose, we assumed the age distribution of the affected and unaffected carriers in our sample (Table 1) and simulated among them risk factors with risk ratios 1.8 and 2.6 and the frequencies for the  $\geq 28$  and  $\geq 29$  CAG cut-points observed in our sample. The data were then analyzed using unweighted Cox regression. We conducted 1000 simulations per model. More details about the simulations are available from the authors of the present report. The power of detecting risk ratios of 1.8 and 2.6 was estimated to be 51% and 92%, respectively, for the sample of *BRCA1* mutation carriers and 28% and 78% for the sample of *BRCA2* mutation carriers.

R version 1.9.0 (R Foundation for Statistical Computing, Vienna, Austria) was used to perform the unweighted Cox regression, and STATA version 7 (Stata Corporation, College Station, TX, USA) was used for the weighted analyses.

## Results

The *AR* CAG length ranged from 8 to 36 repeats. There was little power to assess potential confounding or risk associated with the cut-point  $\geq 30$  CAG repeats, because only 11 *BRCA1* and 11 *BRCA2* carriers had at least one allele of this size. There was no evidence for an association between *AR* CAG repeat length and year of birth, age at menarche, or parity. There was marginal evidence for a preponderance of smaller alleles among affected *BRCA2* carriers who reported using the oral contraceptive pill ( $P = 0.03$ ), but this association was not seen in unaffected individuals or in *BRCA1* affected or unaffected carriers ( $P > 0.2$ ).

The estimated rate ratios associated with *AR* CAG repeat length are given in Tables 2 and 3. Risk estimates using the weighted Cox regression approach were very similar to the

unweighted estimates, and for simplicity the unweighted estimates are shown. No associations were observed for alleles  $\geq 28$  CAG repeats or  $\geq 29$  CAG repeats – cut-points previously reported to be associated with risk. Estimated RRs were close to and not significantly different from 1 (all  $P > 0.3$ ) and were in most instances less than 1. The number of individuals with  $\geq 30$  CAG repeats was too small to provide reliable risk estimates, but point estimates (0.49 [ $P = 0.1$ ] for *BRCA1*, 0.69 [ $P = 0.5$ ] for *BRCA2*) provided no evidence for increased risk associated with these large alleles. When *AR* CAG repeat length was considered as a continuous variable, there was no association either with average repeat length or with the length of the shorter or longer allele ( $P \geq 0.2$ ). There was little difference between the estimates adjusted only for source group and ethnicity, and those adjusted also for year of birth, and hormonal variables oophorectomy, parity, age at menarche and contraceptive pill use. Risk estimates were not markedly different when women with a first primary diagnosis of ovarian cancer were excluded, with a RR (95% CI) for the  $\geq 28$  CAG cut-point of 0.85 (0.49–1.47) for *BRCA1* mutation carriers ( $P = 0.6$ ), and 1.12 (0.055–2.27) for *BRCA2* mutation carriers ( $P = 0.8$ ).

Results using the weighted Cox regression approach indicated that RR estimates were not materially affected by possible ascertainment biases. For example, for the  $\geq 28$  CAG cut-point, the RR (95% CI) adjusted for group and ethnicity was 0.74 (0.33–1.66) for *BRCA1* carriers ( $P = 0.5$ ) and 0.94 (0.32–2.77) for *BRCA2* carriers ( $P = 0.9$ ). For average CAG length, the RR (95% CI) adjusted for group and ethnicity was 1.01 (0.94–1.10) for *BRCA1* carriers ( $P = 0.8$ ) and 0.96 (0.82–1.11) for *BRCA2* carriers ( $P = 0.6$ ). These results are consistent with the findings of Antoniou and coworkers (unpublished data), in which both weighted and unweighted Cox regression analyses give similar estimates when the true RR is 1.0.

There was also no compelling evidence for an effect of mutation position on risk associated with *AR* CAG repeat length. *BRCA1* mutations were firstly divided by position relative to amino acid 1365 (nucleotide 4213), because mutations 5' of this have been reported to exhibit markedly decreased *AR* transactivation ability [11]. The RR (95% CI) for the  $\geq 28$  CAG cut-point analyses were 0.93 (0.53–1.64) for domain 1 ( $P = 0.8$ ) and 0.35 (0.12–1.02) for domain 2 ( $P = 0.06$ ), with marginal evidence for an interaction ( $P = 0.1$ ). *BRCA1* mutations were also divided by position relative to amino acid 1065 (nucleotide 3311), because the 3' end of the *BRCA1* fragment has been shown *in vitro* to bind the *AR* amino-terminal domain containing the CAG-encoded polyglutamine tract [11]. The RR (95% CI) for the  $\geq 28$  CAG cut-point analyses were 0.98 (0.54–1.78) for domain 1 ( $P = 0.9$ ) and 0.45 (0.16–1.23)

**Table 2****Risk associated with AR CAG repeat length amongst BRCA1 mutation carriers**

Risk allele	Adjusted group, ethnicity		Adjusted group, ethnicity and additional variables	
	<i>P</i>	RR (95% CI)	<i>P</i>	RR (95% CI)
AR ≥ 28 CAG	0.3	0.74 (0.42–1.29)	0.6	0.88 (0.53–1.46)
AR ≥ 29 CAG	0.3	0.76 (0.43–1.33)	0.7	0.89 (0.54–1.48)
AR average CAG	0.5	1.02 (0.96–1.09)	0.3	1.03 (0.97–1.10)
AR small CAG	0.3	1.03 (0.97–1.09)	0.2	1.04 (0.98–1.10)
AR large CAG	0.9	1.01 (0.96–1.06)	0.6	1.01 (0.97–1.06)

First primary breast cancer diagnosis was considered an event (status affected), whereas first primary ovarian cancers were censored as unaffected at age of diagnosis, and individuals without breast or ovarian cancer were censored as unaffected at age at interview. All individuals were censored as unaffected at age of prophylactic mastectomy prior to diagnosis/interview. Analyses were adjusted for source group, ethnicity, year of birth and hormonal variables oophorectomy, parity, age at menarche and contraceptive pill use. Oophorectomy and parity were treated as time-dependent variables from age at first variable event. Analyses were conducted using unweighted Cox regression.

**Table 3****Risk associated with AR CAG repeat length amongst BRCA2 mutation carriers**

Risk allele	Adjusted group, ethnicity		Adjusted group, ethnicity and additional variables	
	<i>P</i>	RR (95% CI)	<i>P</i>	RR (95% CI)
AR ≥ 28 CAG	0.8	1.12 (0.55–2.25)	0.9	1.04 (0.47–2.32)
AR ≥ 29 CAG	0.8	0.88 (0.37–2.09)	0.8	0.90 (0.32–2.52)
AR average CAG	0.7	0.98 (0.91–1.06)	1.0	1.00 (0.92–1.09)
AR small CAG	0.6	0.98 (0.90–1.06)	1.0	1.00 (0.92–1.09)
AR large CAG	0.9	0.99 (0.93–1.06)	1.0	1.00 (0.93–1.07)

First primary breast cancer diagnosis was considered an event (status affected), whereas first primary ovarian cancers were censored as unaffected at age of diagnosis, and individuals without breast or ovarian cancer were censored as unaffected at age at interview. All individuals were censored as unaffected at age of prophylactic mastectomy before diagnosis/interview. Analyses were adjusted for source group, ethnicity, year of birth, and hormonal variables oophorectomy, parity, age at menarche, and contraceptive pill use. Oophorectomy and parity were treated as time-dependent variables from age at first variable event. Analyses were conducted using unweighted Cox regression.

for domain 2 ( $P = 0.1$ ), with no evidence for an interaction ( $P = 0.3$ )

There was no convincing rationale for stratification of the *BRCA2* mutation carriers by mutation position, in that there is no published information available with regard to the domains of *BRCA2* required for *BRCA2*–*AR* interaction or to the effect of *BRCA2* mutation position on the *BRCA2*–*AR* interaction. However, because a single report has shown that the *BRCA2* L1042X mutation does not enhance *AR* transactivation [10], mutations 5' to this mutation site might be expected to have similar drastic consequences, and to convey increased risk among carriers with large *AR* CAG alleles. Stratification by mutation position relative to amino acid 1042 (nucleotide 4213) divided the *BRCA2* carrier sample into two subgroups of 42 and 177 individuals. None of the 42 individuals with mutations in domain 1 had alleles with repeat length ≥ 28 CAG, precluding estimates of risk for this subgroup. However, there was no evidence for increased risk among *BRCA2* carriers with mutations in the domain 5' to amino acid

L1024, with a RR (95% CI) for the ≥ 28 CAG cut-point of 1.11 (0.54–2.30) for the 5' domain ( $P = 0.8$ ).

**Discussion**

Our study found no evidence to support the previously reported association of *AR* allele length with increased breast cancer risk in *BRCA1* carriers [7]. The hypothesis-generating study estimated a 1.8-fold risk (95% CI 1.1–3.1) in *BRCA1* carriers with at least one *AR* allele length ≥ 28 CAG repeats, and increasing risks of 2.7-fold and 4.5-fold for the ≥ 29 CAG repeat and ≥ 30 CAG repeat cut-points, respectively [7]. The RR estimated by our study for ≥ 28 repeats was 0.74, and the upper 95% confidence limit (1.28) excludes the effect size reported by Rebbeck and coworkers [7]. Moreover, there was no evidence for increased RRs at the ≥ 29 or ≥ 30 cut-points. Given that we had approximately 80% or more power to detect risk estimates previously reported for the ≥ 29 cut-point [7], these results suggest that if there is any increased risk for large number of CAG repeats among *BRCA1* mutation carriers, then it is of much lower magnitude than was first reported.

Rebbeck and coworkers [7] found no effect of *AR* CAG repeat length when considered as a continuous variable, and our study likewise found no evidence for an association with shorter, larger, or average CAG repeat length.

Other published studies have found no evidence to support an association between *AR* CAG repeat length and breast cancer risk in *BRCA2* mutation carriers [8,9]. Our study also found no evidence in support of an association. Although our sample of 220 *BRCA2* carriers was not sufficiently large to provide precise estimates of risk, the upper 95% confidence limits imply that a 2.5-fold risk associated with  $\geq 28$  or  $\geq 29$  repeat lengths is unlikely.

## Conclusion

Our analyses provide no support for an association between *AR* CAG repeat length and breast cancer risk in either *BRCA1* or *BRCA2* mutation carriers. An increased risk associated with  $\geq 28$  or  $\geq 29$  repeat lengths is not compatible with our data. Weak associations cannot be excluded, but analyses involving much larger numbers of carriers would be required to evaluate this possibility.

## Competing interests

The author(s) declare that they have no competing interests.

## Authors' contributions

ABS was responsible for supervising genotyping design and laboratory work, for data cleaning and analysis, and leading the manuscript preparation. ACA, DLD, NP, DMP and BN assisted in the analytical design and analysis of this study. XC and LK were responsible for assay design and optimization, laboratory work and genotype data cleaning. SP and MRC were responsible for the coordination of the EMBRACE study. PLS assisted with the data management and analysis of this study. GSD, CA and MCS assisted with management and provision of data and DNA from the ABCFS and AJBCS. JLH and GGG initiated the ABCFS, and have been instrumental in the ongoing execution of this study. GC-T initiated and obtained funding for this study, initiated collaborative efforts and was involved in the supervision of laboratory work. DFE initiated the EMBRACE study, and assisted in the development of the analytical design of this study and the manuscript preparation. All authors reviewed the manuscript and offered comments.

## Acknowledgements

We thank all the laboratories that contributed to the identification of mutation carriers. We thank Renee McIlroy for her role in initiating this study, and Heather Thorne, Sandra Picken, Eveline Niedermayer, Jenny Leary, Tracey Davis, Lesley Andrews, Kathy Tucker, Andrea Tesoriero, Sarah Steinborner and Deon Venter for data supply and DNA preparation for this project. We would specifically like to thank Margaret McCredie for her role in the establishment of the ABCFS. We are grateful to the physicians, surgeons and oncologists who endorsed this

project, the interviewing staff, and the many women who participated in this research. KConFaB has been funded by the Kathleen Cuninghame Foundation, National Breast Cancer Foundation, National Health and Medical Research Council (NHMRC), Cancer Council of Victoria, Cancer Council of South Australia, Queensland Cancer Fund, Cancer Council of New South Wales, Cancer Foundation of Western Australian and Cancer Council of Tasmania. The ABCFS and AJBCS were funded by the National Health and Medical Research Council, the Victorian Health Promotion Foundation, the New South Wales Cancer Council, the Peter MacCallum Cancer Institute, the Inkster-Ross Memorial Fund and the National Institute of Health, as part of the Cancer Family Registry for Breast Cancer Study (CA 69638). The EMBRACE study was funded by a project grant from Cancer Research UK. This work is supported by a grant from the NHMRC. ABS is funded by an NHMRC Career Development Award, and GC-T and JLH are NHMRC Senior and Senior Principle Research Fellows, respectively. PLS was funded by a grant from the INHERIT BRCA programme from the Canadian Institute for Health Research. DFE is a Cancer Research UK Principal Research Fellow.

## References

1. Chamberlain NL, Driver ED, Miesfeld RL: **The length and location of CAG trinucleotide repeats in the androgen receptor N-terminal domain affect transactivation function.** *Nucleic Acids Res* 1994, **22**:3181-3186.
2. Irvine RA, Ma H, Yu MC, Ross RK, Stallcup MR, Coetzee GA: **Inhibition of p160-mediated coactivation with increasing androgen receptor polyglutamine length.** *Hum Mol Genet* 2000, **9**:267-274.
3. Wooster R, Mangion J, Eeles R, Smith S, Dowsett M, Averill D, Barrett-Lee P, Easton DF, Ponder BA, Stratton MR: **A germline mutation in the androgen receptor gene in two brothers with breast cancer and Reifenshtein syndrome.** *Nat Genet* 1992, **2**:132-134.
4. Lobaccaro JM, Lumbroso S, Belon C, Galtier-Dereure F, Bringer J, Lesimple T, Heron JF, Pujol H, Sultan C: **Male breast cancer and the androgen receptor gene.** *Nat Genet* 1993, **5**:109-110.
5. Zhu X, Daffada AA, Chan CM, Dowsett M: **Identification of an exon 3 deletion splice variant androgen receptor mRNA in human breast cancer.** *Int J Cancer* 1997, **72**:574-580.
6. Lillie EO, Bernstein L, Ursin G: **The role of androgens and polymorphisms in the androgen receptor in the epidemiology of breast cancer.** *Breast Cancer Res* 2003, **5**:164-173.
7. Rebbeck TR, Kantoff PW, Krithivas K, Neuhausen S, Blackwood MA, Godwin AK, Daly MB, Narod SA, Garber JE, Lynch HT, et al.: **Modification of BRCA1-associated breast cancer risk by the polymorphic androgen-receptor CAG repeat.** *Am J Hum Genet* 1999, **64**:1371-1377.
8. Kadouri L, Easton DF, Edwards S, Hubert A, Kote-Jarai Z, Glaser B, Durocher F, Abeliovich D, Peretz T, Eeles RA: **CAG and GGC repeat polymorphisms in the androgen receptor gene and breast cancer susceptibility in BRCA1/2 carriers and non-carriers.** *Br J Cancer* 2001, **85**:36-40.
9. Dagan E, Friedman E, Paperna T, Carmi N, Gershoni-Baruch R: **Androgen receptor CAG repeat length in Jewish Israeli women who are BRCA1/2 mutation carriers: association with breast/ovarian cancer phenotype.** *Eur J Hum Genet* 2002, **10**:724-728.
10. Shin S, Verma IM: **BRCA2 cooperates with histone acetyltransferases in androgen receptor-mediated transcription.** *Proc Natl Acad Sci USA* 2003, **100**:7201-7206.
11. Yeh S, Hu YC, Rahman M, Lin HK, Hsu CL, Ting HJ, Kang HY, Chang C: **Increase of androgen-induced cell death and androgen receptor transactivation by BRCA1 in prostate cancer cells.** *Proc Natl Acad Sci USA* 2000, **97**:11256-11261.
12. Park JJ, Irvine RA, Buchanan G, Koh SS, Park JM, Tilley WD, Stallcup MR, Press MF, Coetzee GA: **Breast cancer susceptibility gene 1 (BRCA1) is a coactivator of the androgen receptor.** *Cancer Res* 2000, **60**:5946-5949.
13. Apicella C, Andrews L, Hodgson SV, Fisher SA, Lewis CM, Solomon E, Tucker K, Friedlander M, Bankier A, Southey MC, et al.: **Log odds of carrying an ancestral mutation in BRCA1 or BRCA2 for a defined personal and family history in an Ashkenazi Jewish woman (LAMBDA).** *Breast Cancer Res* 2003, **5**:R206-R216.

14. McCredie MR, Dite GS, Giles GG, Hopper JL: **Breast cancer in Australian women under the age of 40.** *Cancer Causes Control* 1998, **9**:189-198.
15. Hopper JL, Chenevix-Trench G, Jolley DJ, Dite GS, Jenkins MA, Venter DJ, McCredie MRE, Giles GG: **Design and analysis issues in a population-based case-control-family study of the genetic epidemiology of breast cancer and the Co-operative Family Registry for Breast Cancer Studies (CFRBCS).** *J Natl Cancer Inst Monogr* 1999, **26**:95-100.
16. Spurdle AB, Dite GS, Chen X, Mayne CJ, Southey MC, Batten LE, Chy H, Trute L, McCredie MR, Giles GG, *et al.*: **Androgen receptor exon 1 CAG repeat length and breast cancer in women before age forty years.** *J Natl Cancer Inst* 1999, **91**:961-966.
17. Huber PJ: **The behaviour of maximum likelihood estimates under non-standard conditions.** In *Fifth Berkeley Symposium in Mathematical Statistics and Probability: 1967* Berkeley, CA: University of California Press; 1967:221-233.
18. Antoniou A, Pharoah PD, Narod S, Risch HA, Eyfjord JE, Hopper JL, Loman N, Olsson H, Johannsson O, Borg A, *et al.*: **Average risks of breast and ovarian cancer associated with BRCA1 or BRCA2 mutations detected in case Series unselected for family history: a combined analysis of 22 studies.** *Am J Hum Genet* 2003, **72**:1117-1130.
19. Tesoriero A, Andersen C, Southey M, Somers G, McKay M, Armes J, McCredie M, Giles G, Hopper JL, Venter D: **De novo BRCA1 mutation in a patient with breast cancer and an inherited BRCA2 mutation.** *Am J Hum Genet* 1999, **65**:567-569.