



Published in final edited form as:

Cancer Epidemiol Biomarkers Prev. 2020 February ; 29(2): 359–367. doi:
10.1158/1055-9965.EPI-19-0506.

Prevalence of Inherited Mutations in Breast Cancer Predisposition Genes among Uganda and Cameroon Women

Babatunde Adedokun^{1,*}, Yonglan Zheng^{1,*}, Paul Ndom², Antony Gakwaya³, Timothy Makumbi⁴, Alicia Y. Zhou⁵, Toshio F. Yoshimatsu¹, Alex Rodriguez⁶, Ravi K. Madduri^{6,7}, Ian T. Foster^{6,7}, Aminah Sallam^{1,8}, Olufunmilayo I. Olopade¹, Dezheng Huo^{1,9}

¹Center for Clinical Cancer Genetics and Global Health, Department of Medicine, The University of Chicago, Chicago, Illinois, USA ²Hôpital Général Yaoundé, Yaoundé, Cameroon ³St. Augustine International University, Kampala, Uganda ⁴Department of Surgery, Mulago Hospital, Kampala, Uganda ⁵Color Genomics, Burlingame, California, USA ⁶Globus, The University of Chicago, Illinois, USA ⁷Data Science and Learning Division, Argonne National Laboratory, Illinois, USA ⁸Yale School of Medicine, New Haven, Connecticut, USA ⁹Department of Public Health Sciences, The University of Chicago, Chicago, Illinois, USA

Abstract

Purpose—Sub-Saharan Africa (SSA) has a high proportion of premenopausal hormone receptor negative breast cancer. Previous studies reported a strikingly high prevalence of germline mutations in *BRCA1* and *BRCA2* among Nigerian breast cancer patients. It is unknown if this exists in other SSA countries.

Methods—Breast cancer cases, unselected for age at diagnosis and family history, were recruited from tertiary hospitals in Kampala, Uganda and Yaoundé, Cameroon. Controls were women without breast cancer recruited from the same hospitals and age-matched to cases. A multi-gene sequencing panel was used to test for germline mutations.

Results—There were 196 cases and 185 controls with mean age of 46.2 and 46.6 years for cases and controls, respectively. Among cases, 15.8% carried a pathogenic or likely pathogenic mutation in a breast cancer susceptibility gene: 5.6% in *BRCA1*, 5.6% in *BRCA2*, 1.5% in *ATM*, 1% in

Corresponding authors: Dr. Dezheng Huo (dhuo@health.bsd.uchicago.edu) and Dr. Olufunmilayo I. Olopade (folopade@medicine.bsd.uchicago.edu).

Author contributions

Conception and design: D. Huo, O.I. Olopade

Development of methodology: Y. Zheng, A.Y. Zhou, T.F. Yoshimatsu, A. Rodriguez, R.K. Madduri

Acquisition of data (provided animals, acquired and managed patients, provided facilities, etc.): P. Ndom. A. Gakwaya, T. Makumbi
Analysis and interpretation of data (e.g., statistical analysis, biostatistics, computational analysis): B. Adedokun, Y. Zheng, A.Y. Zhou, D. Huo

Writing, review, and/or revision of the manuscript: B. Adedokun, Y. Zheng, D. Huo, O.I. Olopade

Administrative, technical, or material support (i.e., reporting or organizing data, constructing databases): T.F. Yoshimatsu, A.

Rodriguez, R.K. Madduri, I.T. Foster, A. Sallam

Study supervision: D. Huo, O.I. Olopade

*Contributed equally

Authors' disclosures of potential conflicts of interest

Alicia Y. Zhou is employed by and owns stock in Color Genomics. Olufunmilayo I. Olopade is an equity stock holder of CancerIQ and Tempus and received grant funding from Color Genomics Foundation. The other authors declare no conflicts of interest.

PALB2, 0.5% in *BARD1*, 0.5% in *CDH1*, and 0.5% in *TP53*. Among controls, 1.6% carried a mutation in one of these genes. Cases were 11-fold more likely to carry a mutation compared to controls (odds ratio=11.34, 95% confidence interval: 3.44–59.06; $P<0.001$). The mean age of cases with *BRCA1* mutations was 38.3 years compared to 46.7 years among other cases without such mutations ($P=0.03$).

Conclusion—Our findings replicate the earlier report of a high proportion of mutations in *BRCA1/2* among patients with symptomatic breast cancer in SSA.

Impact—Given the high burden of inherited breast cancer in SSA countries, genetic risk assessment could be integrated into national cancer control plans.

Keywords

breast cancer; multi-gene sequencing panel; *BRCA1*; *BRCA2*; sub-Saharan Africa

Introduction

The discovery of susceptibility genes for common cancers has remarkably advanced the care of individuals with hereditary cancers and their families. Perhaps the most studied and most clearly understood are the mutational profile of the *BRCA1* and *BRCA2* genes and their role in the management of breast cancer. The lifetime risk of breast and ovarian cancer among *BRCA1* mutation carriers is 57% to 65% and 20% to 50%, respectively; while for *BRCA2*, the risks are 35% to 57% and 5% to 23%, respectively (1,2). Healthy carriers of damaging mutations in high penetrance genes such as *BRCA1* and *BRCA2* genes now have the opportunity for more intensive surveillance for early detection, and could potentially benefit from interventions for primary prevention such as risk reducing surgeries or chemoprevention with Tamoxifen (3,4). Those diagnosed with cancer also benefit from personalized management of their cancer and interventions to reduce second primary cancers (5,6).

The prevalence of damaging mutations in *BRCA1* and *BRCA2* in patients with breast cancer varies by study design and the composition of early-onset cases, cases with strong family history, or a particular cancer subtype, such as triple-negative breast cancer. Mutation frequency is relatively high (15%–55%) among breast cancer cases and families evaluated in cancer risk clinic settings where patients with strong family history are more likely to be referred for risk assessment (7–13). A case series of young patients with breast cancer (but unselected for family history) found 5.9% for *BRCA* mutation prevalence among women younger than 36 years (14), while a prevalence of 11.2% was recently reported in women with triple negative breast cancer (15) and a 23% mutation frequency was reported in young Mexican women with triple negative breast cancer (16).

Population based studies, in which breast cancer patients were recruited regardless of age at diagnosis or family history, gave estimates of *BRCA* mutation prevalence lower than those reported in cancer-risk clinic settings. For example, Malone *et al* reported a 4.7% *BRCA1/2* mutation prevalence in patients ages 35–64 years (17), Newman *et al* reported a 3.3% *BRCA1* mutation frequency in patients younger than 75 years (18), and John *et al* reported a

2.2% *BRCA1* mutation frequency in non-Hispanic white patients younger than 65 years (19). It is well-documented that Ashkenazi Jews have high frequencies of deleterious founder mutations in *BRCA1* and *BRCA2*, with >9% mutation frequency in unselected breast cancer cases (17,19,20). In cancer-free individuals, Ashkenazi Jews had *BRCA1/2* combined frequencies above 2% (20,21), in contrast to 0.6% in the general population (22,23). It is reported that African Americans had slightly lower proportion of *BRCA1/2* mutation compared to European Americans. Malone *et al* (17) reported that 4.0% of African American patients had a mutation in *BRCA1* or *BRCA2*, compared to 5.0% in European Americans. John *et al* (19) found a 1.3% *BRCA1* mutation frequency among African Americans compared to 2.2% among Non-Hispanic whites, but young (<35 years) African Americans had a high *BRCA1* mutation frequency (16.7%).

Breast cancer mortality rate is highest in Sub-Saharan Africa (SSA) in part due to early onset and aggressive disease, poor health infrastructure and lack of access to diagnostics and modern cancer medicines (24–26). The recent advances in cancer genetics and genomics hold great promise for global oncology and could be harnessed to improve cancer outcomes among indigenous Africans. Yet, to date, little is known about the genetic susceptibility for breast cancer among native African women. We have previously reported high proportions of *BRCA1* (7.1%) and *BRCA2* (3.9%) mutations among indigenous Nigerian women with breast cancer unselected for age of cancer onset and family history of the disease (27). Recently, we expanded the study using a multi-gene panel on 1136 cases and 997 controls and found similarly high frequencies of 7.0% and 4.1% for deleterious mutations in *BRCA1* and *BRCA2*, respectively (28). It is unknown if this finding also holds in other SSA countries. Therefore, we examined the burden of inherited breast cancer and the spectrum of germline mutations in breast cancer susceptibility genes using a case-control study in Cameroon and Uganda.

Methods

Study participants

This study is part of the African Breast Cancer Study -- a multi-country epidemiological study on breast cancer risk factors among indigenous African women that began in Nigeria in 1998 and was expanded to Cameroon and Uganda in 2011. Details of the study design and procedures have been reported in previous publications (29,30). Breast cancer cases aged 18 years or older were recruited at the breast and endocrine unit in the department of surgery of the Mulago Hospital in Kampala, Uganda and the department of medical oncology of Yaounde General Hospital in Yaounde, Cameroon. All consecutive cases between 2011 and 2015 were approached and enrolled, regardless of family history and age at onset of disease. In Cameroon, controls were women randomly recruited from the clinics of general medicine and obstetrics and gynecology departments at Yaounde General Hospital, frequency-matched to cases for age (within 5-year-age category) and ethnicity. In Uganda, female controls were randomly recruited from the general outpatient clinics and surgical ward admissions at Mulago Hospital, frequency-matched to cases for age (within 5-year-age category) and ethnicity. At both sites, controls were unselected for their medical conditions (except that no clinically known breast cancer) and they were not relatives of

cases. The study protocol was reviewed by the institutional review boards of the two study sites and the University of Chicago. All study participants provided written informed consent prior to their interview.

Gene selection and panel sequencing

A 30-gene hereditary cancer risk panel developed by Color Genomics (Burlingame, CA) was used for variant detection. Twelve known and candidate breast cancer genes in the panel were included in the present study: *ATM*, *BARD1*, *BRCA1*, *BRCA2*, *BRIP1*, *CDH1*, *CHEK2*, *NBN*, *PALB2*, *PTEN*, *STK11*, and *TP53*. These genes were assessed for variants within coding exons and non-canonical splice regions. High molecular weight genomic DNA was extracted from whole blood and rigorous quality control was conducted. Next-generation sequencing (NGS) procedures were performed at the Color laboratory under CLIA (Clinical Laboratory Improvements Amendments #05D2081492) and CAP (College of American Pathologists #8975161) compliance. NGS library preparation was performed using the Kapa HyperPlus Library Preparation Kit (Kapa Biosciences, Cape Town, South Africa), and target enrichment was performed using Agilent SureSelect XT probes (Agilent, Santa Clara, CA). Sequencing was performed on an Illumina NextSeq 500/550 instrument (Illumina, San Diego, CA) for 150 bp paired-end sequencing (31).

NGS variant calling

Sequence reads were aligned against human reference genome GRCh37.p12 with the Burrows-Wheeler Aligner (BWA-MEM) (32), and duplicate and low-quality reads were removed. Single nucleotide variants (SNVs) and small (2 to 50 bp) insertions and deletions (indels) were called using the GATK HaplotypeCaller module (33), and large (>50 bp) structural variants (SVs) were detected based on read-depth and using dedicated split-read based algorithms (34) at the Color laboratory. A no template control and two positive controls containing a set of known variants were concurrently run within every batch of samples (31). The NGS coverage requirements for reporting were 20X for each base of the reportable range and 50X for 99% of the reportable range. Median coverage was achieved at 200–300X. In parallel, FASTQ files were transferred to University of Chicago (UChicago) through Globus Online (35,36) and germline variants were identified using the ConVarCal analysis toolkit in Globus genomics platform (37,38). The consensus candidate variants were independently called by the Color and UChicago teams that were blinded to the phenotypes of the subjects. The variants were reviewed, discussed, and later classified as variants of uncertain significance (VUS), likely pathogenic, or pathogenic according to the American College of Medical Genetics and Genomics 2015 guidelines, based on criteria that evaluate molecular structural effect, computational prediction, experimental functional study, clinical findings, and population data (39). All variant classifications were approved by an American Board of Medical Genetics and Genomics board-certified medical geneticist at the Color laboratory.

Statistical analysis

Data was analysed using frequencies and chi-square tests. Odds ratios (OR) and exact 95% confidence interval (CI) were calculated to indicate the strength of association between germline mutation and breast cancer risk. The t-test was used to compare age at breast

cancer diagnosis between patients with and without a mutation, and the Fisher's exact test was used to compare mutation frequency between patients with and without family history of breast cancer. Two-sided P value <0.05 was considered statistically significant.

Results

The study included 381 study participants with 196 breast cancer cases and 185 controls. Of these, 187 were enrolled in Uganda and 194 in Cameroon. The mean age of cases and controls was 46.2 years and 46.6 years, respectively. Summary statistics for breast cancer risk factors are shown in Table 1. Of all 135 variants (34 P/LP mutations and 101 VUS) identified in the twelve genes, the majority were SNVs (119, found in 104 women), 15 indels (one per woman) and one SV. Thirty-four P/LP mutations were found in 34 women (one mutation per woman), including 31 cases (15.8%) and 3 controls (1.6%). Of the 34 P/LP mutations, there were 18 SNVs, 15 indels and 1 SV; among them 13 and 11 mutations were found in *BRCA1* and *BRCA2*, respectively (Figure 1).

Among breast cancer cases, most P/LP mutations were found in *BRCA1* ($n=11$, 5.6%) and *BRCA2* ($n=11$, 5.6%), followed by 3 (1.5%) in *ATM*, 2 (1%) in *PALB2*, and 1 each in *BARD1*, *CDHI*, *TP53*, and *CHEK2*. Three controls had P/LP mutations in *BRCA1* ($n=2$, 1.1%) and *BARD1* ($n=1$, 0.5%) (Table 2). There was a strong association between carrying a P/LP mutation in any breast cancer gene and breast cancer risk (OR=11.4, 95% CI: 3.4 – 59.0; $P<0.001$), and also for mutations in either *BRCA1* or *BRCA2* (OR=11.6, 95% CI: 2.8 – 102.5; $P<0.001$) (Table 3). The mean age of breast cancer cases with P/LP *BRCA1* mutations was 38.3 years compared to 46.7 years among other cases without such mutations ($P=0.03$). Of the 13 cases with a positive family history, 4 (30.8%) had a mutation in breast cancer susceptibility genes, compared to 27 of 183 (14.8%) cases without a family history of breast cancer ($P=0.13$).

Table 4 shows the spectrum of pathogenic or likely pathogenic mutations. There was a SV (deletion of exon 2) in *BARD1*. Recurrent mutations were found in *BRCA1* (c.4484G>T, 3 cases; c.2017G>T, 1 case and 1 control; c.4676-1G>C, 1 case and 1 control; c.4986+6T>C, 2 cases), and *ATM* (c.7913G>A, 2 cases). Novel mutations in *BRCA1* among our sample were c.2966_2967del, c.4323_4329del, and in *BRCA2* were c.1053del, c.1964del, c.2937del, c.4693_4694dup, c.5633dup, c600dup, and c.6987_6993del. The *BRCA1* mutation c.1796_1800delCTTAT was reported in our most recent study among Nigerian women (28). The *TP53* variant, c.818G>A, had been reported in the 1000 Genomes database among European populations (Supplementary Table 1).

As would be expected, there were 101 VUS in breast cancer genes found in 96 individuals (25.2%), of which 53 were cases and 43 were controls. Nine VUS in *BRCA1* were found in 7 cases (3.6%) and 2 controls (1.1%), while in *BRCA2*, 14 VUS were found in 7 cases (3.6%) and 7 controls (3.8%). The 72 unique VUS in breast cancer genes and their frequency of occurrence are shown in Table 5. VUS found among women in both Cameroon and Uganda were *ATM* (c.4082A>G, c.131A>G), *BARD1* (c.1067A>T), and *PALB2* (c.365A>G). There were no scenarios where individuals with VUS in *BRCA1* or *BRCA2* also had pathogenic mutations in these genes. However, women with some VUS in *ATM*,

BARD1, *CDH1*, *CHEK2* and *NBN* also had deleterious mutations in the same or other genes (Table 5). Most of the VUS were not reported in the 1000 Genomes database, except the VUS in *BRCA1* (c.923G>C), *BRCA2* (c.7712A>G), *ATM* (c.4082A>G, c.131A>G), *BARD1* (c.1067A>T, c.764A>G, c.155G>A) were found in African populations, *ATM* c.8071C>T was found only in European populations and *BARD1* c.155G>A was found only in American populations of the same database (Supplementary Table).

Discussion

This study has shown a high prevalence (11.2%) of mutations in the *BRCA1* (5.6%) and *BRCA2* genes (5.6%) among women with breast cancer in Uganda and Cameroon, which is similar to our previous report of 11.1% (7.0% in *BRCA1* and 4.1% in *BRCA2*) among Nigerian women (28). Additionally, we found mutations in other breast cancer susceptibility genes, giving an overall mutation frequency of 15.8% among breast cancer patients in Uganda and Cameroon. In addition, there was a high VUS rate which underscores the need for expanded research to resolve the clinical significance of these variants.

The comparable high mutation frequency found among women across three SSA countries suggests a significant burden of heritable risk factors across these countries. Population-based studies such as Malone *et al* (17) reported mutation frequencies of 2.4% and 2.3% in *BRCA1* and *BRCA2*, respectively, in African Americans, while John *et al* 2007 found a mutation frequency of 1.3% in *BRCA1* among African American breast cancer cases. Possibly, the relatively low prevalence of non-genetic risk factors for breast cancer in SSA could explain the higher mutation frequencies among sub-Saharan women. Indigenous African women are younger at the onset of breast cancer, and have a higher prevalence of non-genetic protective factors such as longer breastfeeding duration, late menarche, early onset of childbearing, and higher number of live births compared to women in developed countries (Table 1). This enrichment of heritable breast cancer provides a unique opportunity to develop genetic risk prediction models for breast cancer unique to African ancestry groups and to identify new causal variants for breast cancer that may be targeted for interventions to reduce risk among women of African ancestry.

The consistently high *BRCA1* and *BRCA2* mutation frequencies found among SSA women with breast cancer has significant implications for cancer interventions. The first is the introduction of low cost genetic testing among women in low resource settings. DNA sequencing cost is significantly reduced, and genetic counseling and testing services are now a feasible option in low resource settings such as SSA. However, to our knowledge, there are no guidelines in SSA concerning when BRCA testing should be offered and healthy high risk women continue to die from preventable cancers. Replication of our data from Nigeria in Uganda and Cameroon makes our results more generalizable for Africans than all studies previously primarily conducted among women of European ancestry. Ongoing efforts to integrate genomic testing for population risk stratification as a way to accelerate progress in eradicating breast and ovarian cancers as causes of premature mortality in SSA women should be supported. Improved access to genetic counseling and testing services and interventions to reduce risk are clearly warranted. National governments in SSA can leap frog by adopting technological advances in cancer genetics and genomics to develop

demand and market for cancer prevention services. Many of breast cancers in SSA are triple-negative breast cancer (TNBC), a cancer subtype that is curable when optimal chemotherapy is used in the early stages but become highly resistant and refractory to treatment in advanced stages. Expanding global access to life saving cancer medicines and clinical trials of PARP inhibitors and immunotherapy-based therapies that have shown considerable promise among patients with aggressive young onset breast cancer would promote health equity and accelerate research to understand the genomic basis of treatment resistance in diverse populations (6,40).

Notwithstanding the high mutation prevalence in *BRCA1/2*, the penetrances of *BRCA1/2* in SSA populations are unknown. Previous studies have shown variations in *BRCA1/2* penetrance based on geographic location (41), so it is equally important to estimate penetrances of *BRCA1/2* for better risk assessment and counseling in SSA populations. In addition, the psychosocial consequences and social implications of *BRCA1/2* mutations in the African context have not been studied. More work is needed to develop culturally tailored interventions that promote adoption of genomic testing for comprehensive risk assessment and prevention.

Our finding that the majority of women with deleterious mutations in *BRCA* genes had no family history of breast cancer has been previously reported (27,28,42). Importantly, clinicians should be aware that the absence of a family history of breast cancer does not preclude the presence of deleterious *BRCA* mutations (41). At the same time, it is noteworthy that family history reports in SSA may be less reliable than in developed countries given the low literacy rate, low cancer awareness, and poor utilization of health care services resulting in under-reporting. Other explanations for low family history reports include death from other causes at earlier ages due to lower life expectancies and poor ascertainment of cancer as a cause of death. It is also conceivable that there are other genetic and non-genetic modifiers of risk that modulate the penetrance of pathogenic mutations and VUSs identified in this study.

An appreciable number of mutations in *BRCA1* and *BRCA2* found in this study had not been previously reported, while recurrent mutations were only found in a few women. This finding is consistent with previous studies among SSA women (27,43), suggesting that targeting selected *BRCA1/2* mutations with founder effect may not be a good strategy for genetic testing.

We performed panel testing and found deleterious mutations in other breast cancer susceptibility genes in 4.5% of women, supporting the use of panel testing of multiple genes. While this is an efficient strategy in well-established laboratories, the penetrance of pathogenic mutations in moderate susceptibility genes such as *ATM*, *CHEK2* and *BARD1*, the spectrum of cancer risk, and clinical utility of testing for these genes are less well understood (46). More rigorous evaluation will be needed before clinical guidelines for mutation carriers in these increasingly important moderate susceptibility genes can be developed. Also, the relatively high VUS frequencies found in this study represent a major clinical conundrum (49) because of the diversity or normal variations in African Genomes that have been understudied. VUS has been reported by several studies among African

ancestry women focusing predominantly on early onset or triple-negative breast cancer, (27,50–54) though lower frequencies have been reported in others (55). This underscores the need for larger genomic sequencing studies in Africans.

The limitations of this study include the relatively small sample size and the lack of data on hormone receptor status that would have allowed the evaluation of mutation prevalence by breast cancer subtype. It is noteworthy that the wide confidence intervals around the odds ratio estimates are a consequence of the small sample size and low mutation frequency among controls and thus they should be interpreted with caution.

In conclusion, our findings confirm the earlier report of a high proportion of deleterious mutations in *BRCA1* and *BRCA2* among breast cancer patients in SSA. As most of these women present with advanced breast cancer, there is an urgent need to improve access to genetic testing in national cancer control plans in SSA.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

This project was supported by Susan G. Komen for the Cure (SAC110026 to O.I. Olopade), NIH Commons Credits Pilot Award (CCREQ-00079 to O.I. Olopade), Breast Cancer Research Foundation (D. Huo, O.I. Olopade), and (R01 CA228198 to D. Huo; U01 CA161032 to O.I. Olopade, D. Huo; and OT3 OD025458, R01 HG009018, U24 CA209996 to I.T. Foster), and Department of Energy (DE-AC02-06CH11357 to I.T. Foster). Y. Zheng is supported by Paul Calabresi Career Development Award for Clinical Oncology (K12 CA139160 to O.I. Olopade). We thank Segun C. Jung for testing the ConVarCal platform.

References

1. Chen S, Parmigiani G. Meta-analysis of BRCA1 and BRCA2 penetrance. *J Clin Oncol* 2007;25(11): 1329–33 doi 10.1200/JCO.2006.09.1066. [PubMed: 17416853]
2. Kuchenbaecker KB, Hopper JL, Barnes DR, Phillips KA, Mooij TM, Roos-Blom MJ, et al. Risks of Breast, Ovarian, and Contralateral Breast Cancer for BRCA1 and BRCA2 Mutation Carriers. *JAMA* 2017;317(23):2402–16 doi 10.1001/jama.2017.7112. [PubMed: 28632866]
3. Domchek SM, Friebel TM, Singer CF, Evans DG, Lynch HT, Isaacs C, et al. Association of risk-reducing surgery in BRCA1 or BRCA2 mutation carriers with cancer risk and mortality. *JAMA* 2010;304(9):967–75 doi 10.1001/jama.2010.1237. [PubMed: 20810374]
4. Saslow D, Boetes C, Burke W, Harms S, Leach MO, Lehman CD, et al. American Cancer Society guidelines for breast screening with MRI as an adjunct to mammography. *CA Cancer J Clin* 2007;57(2):75–89. [PubMed: 17392385]
5. Robson M, Im SA, Senkus E, Xu B, Domchek SM, Masuda N, et al. Olaparib for Metastatic Breast Cancer in Patients with a Germline BRCA Mutation. *N Engl J Med* 2017;377(6):523–33 doi 10.1056/NEJMoa1706450. [PubMed: 28578601]
6. Fong PC, Boss DS, Yap TA, Tutt A, Wu P, Mergui-Roelvink M, et al. Inhibition of poly(ADP-ribose) polymerase in tumors from BRCA mutation carriers. *N Engl J Med* 2009;361(2):123–34 doi 10.1056/NEJMoa0900212. [PubMed: 19553641]
7. Shih HA, Couch FJ, Nathanson KL, Blackwood MA, Rebbeck TR, Armstrong KA, et al. BRCA1 and BRCA2 mutation frequency in women evaluated in a breast cancer risk evaluation clinic. *J Clin Oncol* 2002;20(4):994–9 doi 10.1200/JCO.2002.20.4.994. [PubMed: 11844822]

8. Martin AM, Blackwood MA, Antin-Ozerkis D, Shih HA, Calzone K, Colligon TA, et al. Germline mutations in BRCA1 and BRCA2 in breast-ovarian families from a breast cancer risk evaluation clinic. *J Clin Oncol* 2001;19(8):2247–53 doi 10.1200/JCO.2001.19.8.2247. [PubMed: 11304778]
9. Vaziri SA, Krumroy LM, Rostai M, Casey G. Frequency of BRCA1 and BRCA2 mutations in a clinic-based series of breast and ovarian cancer families. *Hum Mutat* 2001;17(1):74 doi 10.1002/1098-1004(2001)17:1<74::AID-HUMU13>3.0.CO;2-I.
10. Couch FJ, DeShano ML, Blackwood MA, Calzone K, Stopfer J, Campeau L, et al. BRCA1 mutations in women attending clinics that evaluate the risk of breast cancer. *N Engl J Med* 1997;336(20):1409–15 doi 10.1056/NEJM199705153362002. [PubMed: 9145677]
11. Nanda R, Schumm LP, Cummings S, Fackenthal JD, Sveen L, Ademuyiwa F, et al. Genetic testing in an ethnically diverse cohort of high-risk women: a comparative analysis of BRCA1 and BRCA2 mutations in American families of European and African ancestry. *JAMA* 2005;294(15):1925–33 doi 10.1001/jama.294.15.1925. [PubMed: 16234499]
12. Weitzel JN, Clague J, Martir-Negron A, Ogaz R, Herzog J, Ricker C, et al. Prevalence and type of BRCA mutations in Hispanics undergoing genetic cancer risk assessment in the southwestern United States: a report from the Clinical Cancer Genetics Community Research Network. *J Clin Oncol* 2013;31(2):210–6 doi 10.1200/JCO.2011.41.0027. [PubMed: 23233716]
13. Greenup R, Buchanan A, Lorizio W, Rhoads K, Chan S, Leedom T, et al. Prevalence of BRCA mutations among women with triple-negative breast cancer (TNBC) in a genetic counseling cohort. *Ann Surg Oncol* 2013;20(10):3254–8 doi 10.1245/s10434-013-3205-1. [PubMed: 23975317]
14. Peto J, Collins N, Barfoot R, Seal S, Warren W, Rahman N, et al. Prevalence of BRCA1 and BRCA2 gene mutations in patients with early-onset breast cancer. *J Natl Cancer Inst* 1999;91(11):943–9. [PubMed: 10359546]
15. Couch FJ, Hart SN, Sharma P, Toland AE, Wang X, Miron P, et al. Inherited mutations in 17 breast cancer susceptibility genes among a large triple-negative breast cancer cohort unselected for family history of breast cancer. *J Clin Oncol* 2015;33(4):304–11 doi 10.1200/JCO.2014.57.1414. [PubMed: 25452441]
16. Villarreal-Garza C, Weitzel JN, Llacuachaqui M, Sifuentes E, Magallanes-Hoyos MC, Gallardo L, et al. The prevalence of BRCA1 and BRCA2 mutations among young Mexican women with triple-negative breast cancer. *Breast Cancer Res Treat* 2015;150(2):389–94 doi 10.1007/s10549-015-3312-8. [PubMed: 25716084]
17. Malone KE, Daling JR, Doody DR, Hsu L, Bernstein L, Coates RJ, et al. Prevalence and predictors of BRCA1 and BRCA2 mutations in a population-based study of breast cancer in white and black American women ages 35 to 64 years. *Cancer Res* 2006;66(16):8297–308 doi 10.1158/0008-5472.CAN-06-0503. [PubMed: 16912212]
18. Newman B, Mu H, Butler LM, Millikan RC, Moorman PG, King MC. Frequency of breast cancer attributable to BRCA1 in a population-based series of American women. *JAMA* 1998;279(12):915–21. [PubMed: 9544765]
19. John EM, Miron A, Gong G, Phipps AI, Felberg A, Li FP, et al. Prevalence of pathogenic BRCA1 mutation carriers in 5 US racial/ethnic groups. *JAMA* 2007;298(24):2869–76 doi 10.1001/jama.298.24.2869. [PubMed: 18159056]
20. Struewing JP, Hartge P, Wacholder S, Baker SM, Berlin M, McAdams M, et al. The risk of cancer associated with specific mutations of BRCA1 and BRCA2 among Ashkenazi Jews. *N Engl J Med* 1997;336(20):1401–8 doi 10.1056/NEJM199705153362001. [PubMed: 9145676]
21. Bahar AY, Taylor PJ, Andrews L, Proos A, Burnett L, Tucker K, et al. The frequency of founder mutations in the BRCA1, BRCA2, and APC genes in Australian Ashkenazi Jews: implications for the generality of U.S. population data. *Cancer* 2001;92(2):440–5. [PubMed: 11466700]
22. Maxwell KN, Domchek SM, Nathanson KL, Robson ME. Population Frequency of Germline BRCA1/2 Mutations. *J Clin Oncol* 2016;34(34):4183–5 doi 10.1200/JCO.2016.67.0554.
23. Thompson ER, Rowley SM, Li N, McInerney S, Devereux L, Wong-Brown MW, et al. Panel Testing for Familial Breast Cancer: Calibrating the Tension Between Research and Clinical Care. *J Clin Oncol* 2016;34(13):1455–9 doi 10.1200/JCO.2015.63.7454. [PubMed: 26786923]

24. Kantelhardt EJ, Muluken G, Sefonias G, Wondimu A, Gebert HC, Unverzagt S, et al. A Review on Breast Cancer Care in Africa. *Breast Care (Basel)* 2015;10(6):364–70 doi 10.1159/000443156. [PubMed: 26989354]
25. Brinton LA, Figueroa JD, Awuah B, Yarney J, Wiawe S, Wood SN, et al. Breast cancer in Sub-Saharan Africa: opportunities for prevention. *Breast Cancer Res Treat* 2014;144(3):467–78 doi 10.1007/s10549-014-2868-z. [PubMed: 24604092]
26. Vanderpuye V, Grover S, Hammad N, Prabhakar Pooja, Simonds H, Olopade F, et al. An update on the management of breast cancer in Africa. *Infect Agent Cancer* 2017;12:13 doi 10.1186/s13027-017-0124-y. [PubMed: 28228841]
27. Fackenthal JD, Zhang J, Zhang B, Zheng Y, Hagos F, Burrill DR, et al. High prevalence of BRCA1 and BRCA2 mutations in unselected Nigerian breast cancer patients. *Int J Cancer* 2012;131(5):1114–23 doi 10.1002/ijc.27326. [PubMed: 22034289]
28. Zheng Y, Walsh T, Gulsuner S, Casadei S, Lee MK, Ogundiran TO, et al. Inherited Breast Cancer in Nigerian Women. *J Clin Oncol* 2018;36(28):2820–5 doi 10.1200/JCO.2018.78.3977. [PubMed: 30130155]
29. Qian F, Ogundiran T, Hou N, Ndom P, Gakwaya A, Jombwe J, et al. Alcohol consumption and breast cancer risk among women in three sub-Saharan African countries. *PLoS One* 2014;9(9):e106908 doi 10.1371/journal.pone.0106908. [PubMed: 25198723]
30. Hou N, Ndom P, Jombwe J, Ogundiran T, Ademola A, Morhason-Bello I, et al. An epidemiologic investigation of physical activity and breast cancer risk in Africa. *Cancer Epidemiol Biomarkers Prev* 2014;23(12):2748–56 doi 10.1158/1055-9965.EPI-14-0675. [PubMed: 25242052]
31. Neben CL, Zimmer AD, Stedden W, van den Akker J, O'Connor R, Chan RC, et al. Multi-Gene Panel Testing of 23,179 Individuals for Hereditary Cancer Risk Identifies Pathogenic Variant Carriers Missed by Current Genetic Testing Guidelines. *J Mol Diagn* 2019;21(4):646–57 doi 10.1016/j.jmoldx.2019.03.001. [PubMed: 31201024]
32. Li H 2013 20 Aug 2017. Aligning sequence reads, clone sequences and assembly contigs with BWA-MEM [Internet]. arXiv [q-bio.GN] 20 8 2017.
33. McKenna A, Hanna M, Banks E, Sivachenko A, Cibulskis K, Kernysky A, et al. The Genome Analysis Toolkit: a MapReduce framework for analyzing next-generation DNA sequencing data. *Genome Res* 2010;20(9):1297–303 doi 10.1101/gr.107524.110. [PubMed: 20644199]
34. van den Akker J, Mishne G, Zimmer AD, Zhou AY. A machine learning model to determine the accuracy of variant calls in capture-based next generation sequencing. *BMC Genomics* 2018;19(1):263 doi 10.1186/s12864-018-4659-0. [PubMed: 29665779]
35. Chard K, Tuecke S, Foster I. Efficient and secure transfer, synchronization, and sharing of big data. *IEEE Cloud Computing* 2014;1(3):46–55.
36. Madduri RK, Sulakhe D, Lacinski L, Liu B, Rodriguez A, Chard K, et al. Experiences Building Globus Genomics: A Next-Generation Sequencing Analysis Service using Galaxy, Globus, and Amazon Web Services. *Concurrency and computation : practice & experience* 2014;26(13):2266–79 doi 10.1002/cpe.3274. [PubMed: 25342933]
37. Zheng YRA, Jung SC, Yoshimatsu TF, Madduri RK, Dave UJ, Foster I, Olopade OI. ConVarCal Facilitates Robust Massive Parallel Sequencing Variant Calling. Poster. The 6th Annual Translational Bioinformatics Conference Jeju, South Korea 2016.
38. Zheng YYT, Rodriguez A, Madduri RK, Dave PJ, Olopade OI. ConVarCal: A Reliable and Robust Platform for Next-Generation Sequencing Variants Identification Poster. 65th Annual Meeting of The American Society of Human Genetics (ASHG) Baltimore, Maryland 2015.
39. Richards S, Aziz N, Bale S, Bick D, Das S, Gastier-Foster J, et al. Standards and guidelines for the interpretation of sequence variants: a joint consensus recommendation of the American College of Medical Genetics and Genomics and the Association for Molecular Pathology. *Genet Med* 2015;17(5):405–24 doi 10.1038/gim.2015.30. [PubMed: 25741868]
40. Lord CJ, Ashworth A. PARP inhibitors: Synthetic lethality in the clinic. *Science* 2017;355(6330):1152–8 doi 10.1126/science.aam7344. [PubMed: 28302823]
41. Fackenthal JD, Olopade OI. Breast cancer risk associated with BRCA1 and BRCA2 in diverse populations. *Nat Rev Cancer* 2007;7(12):937–48 doi 10.1038/nrc2054. [PubMed: 18034184]

42. Hopper JL, Chenevix-Trench G, Jolley DJ, Dite GS, Jenkins MA, Venter DJ, et al. 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. [PubMed: 10854492]
43. Zhang J, Fackenthal JD, Zheng Y, Huo D, Hou N, Niu Q, et al. Recurrent BRCA1 and BRCA2 mutations in breast cancer patients of African ancestry. *Breast Cancer Res Treat* 2012;134(2):889–94 doi 10.1007/s10549-012-2136-z. [PubMed: 22739995]
44. Rebbeck TR, Friebel TM, Friedman E, Hamann U, Huo D, Kwong A, et al. Mutational spectrum in a worldwide study of 29,700 families with BRCA1 or BRCA2 mutations. *Hum Mutat* 2018;39(5): 593–620 doi 10.1002/humu.23406. [PubMed: 29446198]
45. Wang S, Ogundiran T, Ademola A, Olayiwola OA, Adeoye A, Sofoluwe A, et al. Development of a Breast Cancer Risk Prediction Model for Women in Nigeria. *Cancer Epidemiol Biomarkers Prev* 2018;27(6):636–43 doi 10.1158/1055-9965.EPI-17-1128. [PubMed: 29678902]
46. West AH, Blazer KR, Stoll J, Jones M, Weipert CM, Nielsen SM, et al. Clinical interpretation of pathogenic ATM and CHEK2 variants on multigene panel tests: navigating moderate risk. *Fam Cancer* 2018;17(4):495–505 doi 10.1007/s10689-018-0070-x. [PubMed: 29445900]
47. Turnbull C, Mirugaesu N, Eeles R. Radiotherapy and genetic predisposition to breast cancer. *Clin Oncol (R Coll Radiol)* 2006;18(3):257–67. [PubMed: 16605057]
48. Iannuzzi CM, Atencio DP, Green S, Stock RG, Rosenstein BS. ATM mutations in female breast cancer patients predict for an increase in radiation-induced late effects. *Int J Radiat Oncol Biol Phys* 2002;52(3):606–13. [PubMed: 11849780]
49. Eccles DM, Mitchell G, Monteiro AN, Schmutzler R, Couch FJ, Spurdle AB, et al. BRCA1 and BRCA2 genetic testing-pitfalls and recommendations for managing variants of uncertain clinical significance. *Ann Oncol* 2015;26(10):2057–65 doi 10.1093/annonc/mdv278. [PubMed: 26153499]
50. Churpek JE, Walsh T, Zheng Y, Moton Z, Thornton AM, Lee MK, et al. Inherited predisposition to breast cancer among African American women. *Breast Cancer Res Treat* 2015;149(1):31–9 doi 10.1007/s10549-014-3195-0. [PubMed: 25428789]
51. Kurian AW. BRCA1 and BRCA2 mutations across race and ethnicity: distribution and clinical implications. *Curr Opin Obstet Gynecol* 2010;22(1):72–8 doi 10.1097/GCO.0b013e328332dca3. [PubMed: 19841585]
52. Ricks-Santi L, McDonald JT, Gold B, Dean M, Thompson N, Abbas M, et al. Next Generation Sequencing Reveals High Prevalence of BRCA1 and BRCA2 Variants of Unknown Significance in Early-Onset Breast Cancer in African American Women. *Ethn Dis* 2017;27(2):169–78 doi 10.18865/ed.27.2.169. [PubMed: 28439188]
53. Pal T, Bonner D, Cragun D, Monteiro AN, Phelan C, Servais L, et al. A high frequency of BRCA mutations in young black women with breast cancer residing in Florida. *Cancer* 2015;121(23): 4173–80 doi 10.1002/cncr.29645. [PubMed: 26287763]
54. Pal T, Bonner D, Kim J, Monteiro AN, Kessler L, Royer R, et al. Early onset breast cancer in a registry-based sample of African-american women: BRCA mutation prevalence, and other personal and system-level clinical characteristics. *Breast J* 2013;19(2):189–92 doi 10.1111/tbj. 12083. [PubMed: 23320992]
55. Sharma P, Klemp JR, Kimler BF, Mahnken JD, Geier LJ, Khan QJ, et al. Germline BRCA mutation evaluation in a prospective triple-negative breast cancer registry: implications for hereditary breast and/or ovarian cancer syndrome testing. *Breast Cancer Res Treat* 2014;145(3): 707–14 doi 10.1007/s10549-014-2980-0. [PubMed: 24807107]
56. Felix GES, Zheng Y, Olopade OI. Mutations in context: implications of BRCA testing in diverse populations. *Fam Cancer* 2018;17(4):471–83 doi 10.1007/s10689-017-0038-2. [PubMed: 28918466]

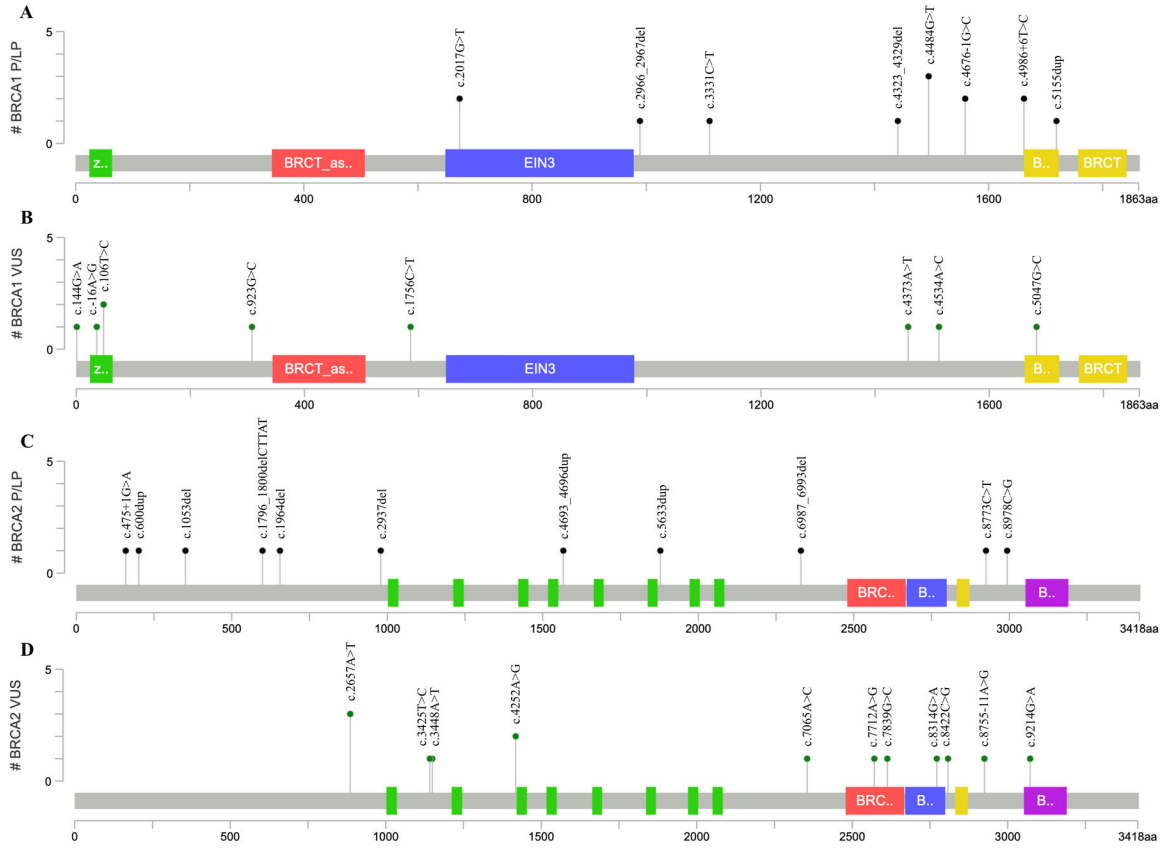


Figure 1. Deleterious mutations and VUS in *BRCA1* and *BRCA2* genes. Distribution of *BRCA1* P/LP (A), *BRCA1* VUS (B), *BRCA2* P/LP (C) and *BRCA2* VUS (D). Variants are displayed along the protein. Length of vertical lines reflects the number of events.

Table 1:

Characteristics of women with breast cancer and controls in Uganda and Cameroon

Variable	Cases (n = 196)	Controls (n = 185)
	Mean (SD)	
Age (years)	46.2 (12.4)	46.6 (11.5)
Height (cm)	162.6 (7.6)	163.2 (7.3)
Weight (kg)	68.8 (14.2)	72.4 (13.5)
Body mass index (kg/m ²)	25.9 (5.2)	27.2 (5.0)
Lifetime breastfeeding duration (months)	70.8 (62.3)	62.3 (45.9)
Age at menarche (years)	14.4 (1.5)	14.4(1.6)
Number of live births	4.2 (2.8)	4.3 (2.7)
Age at first live birth (years)	22.4 (5.6)	22.1 (5.6)
	n. (%)	
Country and ethnicity*		
<i>Cameroon</i>	<i>91 (46.4)</i>	<i>101 (54.6)</i>
Cameroonian Bantu	49 (25.5)	56 (30.4)
Cameroonian Semi-Bantu	34 (17.7)	43 (23.4)
Other Cameroon	8 (4.2)	2 (1.1)
<i>Uganda</i>	<i>101 (53.6)</i>	<i>83 (45.1)</i>
Bagandan	43 (22.4)	41 (22.3)
Other Ugandan	58 (30.2)	42 (22.8)
Family history of breast cancer	13 (6.6)	16 (8.7)
Lifetime alcohol use	96 (49.0)	100 (58.4)
Hormonal contraceptive use	73 (38.0)	87 (48.3)
Premenopausal	131 (66.8)	124 (67.0)
Benign breast disease	27 (13.8)	12 (6.5)

* Five respondents gave 'Don't know' responses and were excluded.

Table 2:

Frequency of deleterious mutations in genes among women in Uganda and Cameroon

Gene	Cases Frequency (%)	Controls Frequency (%)
Overall	(n=196)	(n=185)
<i>BRCA1</i>	11 (5.6)	2 (1.1)
<i>BRCA2</i>	11 (5.6)	0
<i>PALB2</i>	2 (1.0)	0
<i>TP53</i>	1 (0.5)	0
<i>ATM</i>	3 (1.5)	0
<i>CDH1</i>	1 (0.5)	0
<i>CHEK2</i>	1 (0.5)	0
<i>BARD1</i>	1 (0.5)	1 (0.5)
Total	31 (15.8)	3 (1.6)
Cameroon	(n=93)	(n=101)
<i>BRCA1</i>	8 (8.6)	2 (2.0)
<i>BRCA2</i>	4 (4.3)	0
<i>PALB2</i>	1 (1.1)	0
<i>TP53</i>	0	0
<i>ATM</i>	2 (2.2)	0
<i>CDH1</i>	1 (1.1)	0
<i>CHEK2</i>	1 (1.1)	0
<i>BARD1</i>	0	1 (1.0)
Total	17 (18.3)	3(3.0)
Uganda	(n=103)	(n=84)
<i>BRCA1</i>	3 (2.9)	0
<i>BRCA2</i>	7 (6.8)	0
<i>PALB2</i>	1 (1.0)	0
<i>TP53</i>	1 (1.0)	0
<i>ATM</i>	1 (1.0)	0
<i>CDH1</i>	0	0
<i>CHEK2</i>	0	0
<i>BARD1</i>	1 (1.0)	0
Total	14 (13.6)	0

Table 3:

Associations between carrying pathogenic or likely pathogenic mutations with breast cancer risk, family history of breast cancer, and age at diagnosis

	Mutation frequency (%)	OR (95% CI)	P value
P/LP mutation in <i>BRCA1/2</i>			
Cases (n=196)	22 (11.2)	11.6 (2.8–102.5)	<0.001
Controls (n=185)	2 (1.1)	1.0 (ref.)	
P/LP mutation in any breast cancer gene			
Cases (n=196)	31 (15.8)	11.4 (3.4–59.0)	<0.001
Controls (n=185)	3 (1.6)	1.0 (ref.)	
P/LP mutation in any breast cancer gene			
Cases with FH of breast cancer (n=13)	4 (30.8)		0.13
Cases without FH of breast cancer (n=183)	27 (14.8)		
	<u>Mean (SD)</u>		<u>P value</u>
Age of breast cancer diagnosis			
Cases with <i>BRCA1</i> P/LP mutation (n=11)	38.3 (10.6)		0.03
Cases without <i>BRCA1</i> P/LP mutation (n=185)	46.7 (12.4)		

FH, family history; L, pathogenic; LP, likely pathogenic; OR, odds ratio; CI, confidence intervals.

Table 4:

Spectrum of pathogenic or likely pathogenic mutations in breast cancer susceptibility genes among women in Uganda and Cameroon[†]

Gene	Nucleotide change (number of occurrences)	Protein change	Age [‡]	Ethnicity	Family history	Status	Previous reports [§]
<i>BRCA1</i>	c.2017G>T (2)	p.Glu673*	20	Semi-Bantu	No	Case	USA
			47	Semi-Bantu	Yes	Control	
	c.2966_2967del (1)	p.Phe989Cysfs*2	27	Baganda	No	Case	None
	c.3331C>T (1)	p.Gln1111*	34	Other Uganda	No	Case	Singapore, USA
	c.4323_4329del (1)	p.Asp1441Glu fs*13	45	Baganda	No	Case	None
			c.4484G>T (3)	p.Arg1495Met	35	Bantu	No
	36	Bantu			No	Case	
	37	Bantu			No	Case	
	c.4676-1G>C (2)		40	Bantu	No	Case	Clinvar
			46	Bantu	No	Control	
	c.4986+6T>C (2)		33	Other Cameroon	No	Case	Peru, Germany, USA, Canada, France
			56	Other Cameroon	Yes	Case	
	c.5155dup (1)	p.Val1719Glyfs*6	52	Semi-Bantu	No	Case	Germany
<i>BRCA2</i>	c.1053del (1)	p.Lys351Asnfs*16	51	Other Uganda	No	Case	None
	c.1796_1800delCTTAT (1)	p.Ser599*	28	Other Uganda	No	Case	Italy, Holland, Sweden, UK, USA, Australia, Canada, France, Germany
	c.1964del (1)	p.Pro655Glnfs*5	44	Bantu	No	Case	Clinvar
	c.2937del (1)	p.Ile979Metfs*12	69	Semi-Bantu	Yes	Case	None
	c.4693_4696dup (1)	p.Thr1566Lysfs*10	55	Semi-Bantu	No	Case	None
	c.475+1G>A (1)		54	Other Uganda	No	Case	Italy, USA
	c.5633dup (1)	p.Asn1878Lysfs*4	60	Other Uganda	No	Case	None
	c.600dup (1)	p.Pro201Thrfs*5	52	Other Uganda	No	Case	None
	c.6987_6993del (1)	p.Ile2330Valfs*35	41	Other Uganda	No	Case	None
	c.8773C>T (1)	p.Gln2925*	26	Bantu	Yes	Case	Clinvar
	c.8978C>G (1)	p.Ser2993*	61	Other Uganda	No	Case	Clinvar
	<i>CDH1</i>	c.2296-1G>A (1)		30	Bantu	Yes	Case
<i>CHEK2</i>	c.470T>C (1)	p.Ile157Thr	72	Cameroon, ethnicity missing	No	Case	Clinvar
<i>PALB2</i>	c.419del (1)	p.Lys140Serfs*37	31	Bantu	No	Case	None
			40	Baganda	No	Case	Clinvar
<i>TP53</i>	c.818G>A (1)	p.Arg273His	36	Baganda	No	Case	Clinvar
<i>ATM</i>	c.7913G>A (2)	p.Trp2638*	44	Semi-Bantu	No	Case	Clinvar
			49	Semi-Bantu	No	Case	
	c.8833_8834delCT (1)	p.Leu2945Valfs*10	35	Other Uganda	No	Case	Clinvar
<i>BARD1</i>	c.1573dup (1)	p.Ile525Asnfs*12	37	Bantu	No	Control	None

Gene	Nucleotide change (number of occurrences)	Protein change	Age [‡]	Ethnicity	Family history	Status	Previous reports [§]
	deletion of exon 2 (1)		58	Other Uganda	No	Case	None

[‡]Three mutations (c.4676-1G>C in *BRCA1*, c.475+1G>A in *BRCA2*, c.2296-1G>A in *CDHI*) are considered likely pathogenic, while others are considered pathogenic.

[‡]Age at diagnosis (cases) or interview (controls) in years.

[§]Checked using three recent publications (10,28,56) and ClinVar database (<http://www.clinvar.com/>)

Table 5:

Variants of unknown significance in breast cancer susceptibility genes among women in Uganda and Cameroon

Gene	Nucleotide position	Country	Number of occurrence	Protein change	Co-occurrence with pathogenic allele	
<i>BRCA1</i>	c.4373A>T	Cameroon	1	p.Gln1458Leu		
	c.1756C>T	Cameroon	1	p.Pro586Ser		
	c.144G>A	Both in Uganda	2	p.Met48Ile		
	c.923G>C	Uganda	1	p.Ser308Thr		
	c.106T>C	Uganda	1	p.Ser36Pro		
	c.4534A>C	Uganda	1	p.Ser1512Arg		
	c.5047G>C	Uganda	1	p.Glu1683Gln		
	c.-16A>G	Uganda	1			
<i>BRCA2</i>	c.7839G>C	Cameroon	1	p.Lys2613Asn		
	c.7712A>G	Uganda	1	p.Glu2571Gly		
	c.7065A>C	Cameroon	1	p.Glu2355Asp		
	c.2657A>T	All in Uganda	3	p.Asn886Ile		
	c.4252A>G	Both in Uganda	2	p.Ile1418Val		
	c.3448A>T	Uganda	1	p.Thr1150Ser		
	c.8422C>G	Uganda	1	p.Leu2808Val		
	c.8314G>A	Uganda	1	p.Glu2772Lys		
	c.8755-11A>G	Uganda	1	IVS21-11A>G		
	c.9214G>A	Uganda	1	p.Val3072Met		
	c.3425T>C	Uganda	1	p.Phe1142Ser		
	<i>ATM</i>	c.3743A>G	Cameroon	1	p.Tyr1248Cys	
		c.4082A>G	4 in Cameroon, 1 in Uganda	5	p.Gln1361Arg	
c.6343G>A		Cameroon	1	p.Val2115Ile		
c.5660C>T		Both in Cameroon	2	p.Ala1887Val		
c.3560C>G		Cameroon	1	p.Pro1187Arg	<i>BRCA2</i> c.8773C>T	
c.131A>G		1 in Cameroon, 7 in Uganda	8	p.Asp44Gly		
c.3978C>A		Cameroon	1	p.Asn1326Lys		
c.7552C>T		Cameroon	1	p.Pro2518Ser		
c.3031A>G		Cameroon	1	p.Thr1011Ala		
c.3035G>A		Uganda	1	p.Arg1012Lys		
c.5972A>G		Both in Uganda	2	p.Glu1991Gly		
c.2150G>A		Uganda	1	p.Arg717Gln		
c.8071C>T		Uganda	1	p.Arg2691Cys		
c.2771G>A		Uganda	1	p.Arg924Gln		
c.4329C>A		Uganda	1	p.His1443Gln		
c.492G>T	Uganda	1	p.Trp164Cys			

Gene	Nucleotide position	Country	Number of occurrence	Protein change	Co-occurrence with pathogenic allele
	c.4894A>G	Uganda	1	p.Met1632Val	
	c.268A>G	Uganda	1	p.Arg90Gly	
	c.6543G>T	Cameroon	1	p.Glu2181Asp	
<i>BARD1</i>	c.1718T>C	Cameroon	1	p.Ile573Thr	
	c.2296T>C	Cameroon	1	p.Cys766Arg	
	c.1993G>A	Cameroon	1	p.Glu665Lys	
	c.1067A>T	1 in Cameroon, 1 in Uganda	2	p.Asn356Ile	
	c.764A>G	Cameroon	1	p.Asn255Ser	
	c.155G>A	Cameroon	1	p.Arg52His	
	c.1148T>A	Both in Uganda	2	p.Met383Lys	<i>BRCA2</i> c.8978C>G
	c.1439T>C	Uganda	1	p.Leu480Ser	
	c.188T>C	Uganda	1	p.Leu63Ser	
<i>BRIP1</i>	c.2803G>T	Cameroon	1	p.Val935Leu	
	c.2867C>T	Both in Cameroon	2	p.Ser956Leu	
	c.628C>T	Uganda	1	p.Pro210Ser	
	c.854A>G	Both in Uganda	2	p.His285Arg	
<i>CDH1</i>	c.377C>T	Cameroon	1	p.Pro126Leu	
	c.225C>G	Both in Cameroon	2	p.Phe75Leu	
	c.1996A>C	Cameroon	1	p.Asn666His	<i>CDH1</i> c.2296-1G>A
	c.1961C>T	Cameroon	1	p.Pro654Leu	
	c.1136C>T	Uganda	1	p.Thr379Met	
	c.2254G>A	Uganda	1	p.Val752Ile	
	c.865G>A	Uganda	1	p.Ala289Thr	
<i>CHEK2</i>	c.164C>T	Cameroon	1	p.Ser55Phe	<i>BRCA2</i> c.4693_4696dup
	c.1169A>G	Uganda	1	p.Tyr390Cys	
<i>NBN</i>	c.1481A>C	Cameroon	1	p.Gln494Pro	
	c.1711A>G	All in Uganda	3	p.Lys571Glu	<i>ATM</i> c.8833_8834delICT
<i>PALB2</i>	c.949A>C	Both in Cameroon	2	p.Thr317Pro	
	c.3211T>C	Cameroon	1	p.Phe1071Leu	
	c.365A>G	2 in Cameroon, 2 in Uganda	4	p.Asp122Gly	
	c.821C>T	Uganda	1	p.Thr274Ile	
	c.610T>A	Uganda	1	p.Ser204Thr	
<i>PTEN</i>	c.*13C>T	Uganda	1		
	c.-19C>G	Uganda	1		
<i>STK11</i>	c.1229C>T	Cameroon	1	p.Ala410Val	
	c.1253G>C	Uganda	1	p.Cys418Ser	
<i>TP53</i>	c.1120G>C	Both in Uganda	2	p.Gly374Arg	