

Review

# Germline Missense Variants in *BRCA1*: New Trends and Challenges for Clinical Annotation

Volha A. Golubeva, Thales C. Nepomuceno and Alvaro N.A. Monteiro \*

Cancer Epidemiology Program, H. Lee Moffitt Cancer Center and Research Institute, Tampa, FL 33612, USA

\*Correspondence: alvaro.monteiro@moffitt.org; Tel.: +1-813-745-6321

**Abstract:** Genetic testing allows for identification of germline DNA variations which are associated with a significant increase in risk of developing breast and ovarian cancer. Detection of a *BRCA1* or *BRCA2* pathogenic variant triggers several clinical management actions, which may include increased surveillance and prophylactic surgery for healthy carriers or treatment with PARP inhibitor therapy for carriers diagnosed with cancer. Thus, standardized validated criteria for annotation of *BRCA1* and *BRCA2* variants according to their pathogenicity are necessary to support clinical decision making and ensure improved outcomes. Upon detection, variants whose pathogenicity can be inferred by the genetic code are typically classified as pathogenic, likely pathogenic, likely benign, or benign. Variants whose impact on function cannot be directly inferred by the genetic code are labeled as Variants of Uncertain Clinical Significance (VUS) and are evaluated by multifactorial likelihood models that use personal and family history of cancer, segregation data, prediction tools, and co-occurrence with a pathogenic *BRCA* variant. Missense variants, coding alterations that replace a single amino acid residue with another, are a class of variants for which determination of clinical relevance is particularly challenging. Here, we discuss current issues in variant classification by following a typical life cycle of a *BRCA1* missense variant through detection, annotation and information dissemination. Advances in massively parallel sequencing have led to a substantial increase in VUS findings. Although comprehensive assessment and classification of missense variants according to their pathogenicity remains the bottle neck, new developments in functional analysis, high throughput assays, data sharing, and statistical models are rapidly changing this scenario.

**Keywords:** *BRCA1*; variants of uncertain clinical significance; VUS; germline variants; hereditary breast and ovarian cancer; breast cancer; genetic testing, ovarian cancer; variant classification; clinical annotation

---

## 1. Introduction

Breast cancer (BC) is the leading cause of cancer death among women worldwide and second in the U.S. [1,2]. Common risk factors for breast cancer include breast density, older age, family or personal history of breast cancer, lifetime hormonal exposure of breast tissue (early menarche, late menopause, and hormone use) and behavioral factors among others (smoking, alcohol consumption, obesity, physical inactivity, poor diet, stress and anxiety) [3]. According to the International Agency for Research on Cancer, ovarian cancer (OC) ranks eighth among cancer deaths in women worldwide and fifth in the U.S. [4]. Risk factors for OC are linked to older age, obesity and personal or family history of OC. Moreover, hormone therapy, late full-term pregnancy (after 35 years), or not having given birth also increase the risk of OC development [4].

The Hereditary Breast and Ovarian Cancer (HBOC) syndrome [OMIM 604370 and 612555] is a *BRCA1*- or *BRCA2*-linked genetic disorder associated with high risk of developing BC and OC. Hereditary breast cancers constitute about 5-10% of all BC cases, and pathogenic variants in the high-risk ( $RR \geq 4$ ) breast cancer susceptibility genes *BRCA1* [OMIM 113705] and *BRCA2* [OMIM 600185] account for up to 50% (0.7-29% *BRCA1* and 1.5-25% *BRCA2*) of all hereditary breast cancers

[5]. Germline pathogenic variants in *BRCA1* and *BRCA2* account for about 14% of all epithelial ovarian cancers and 16.6% of high-grade serous ovarian cancers [6]. Carriers of a pathogenic variant in the *BRCA1* gene have 72% cumulative risk up to 80 years of developing BC (5-fold increase), and 44% for OC (30-fold increase) [7]. The U.S. National Comprehensive Cancer Network (NCCN) guidelines advise who should be tested for *BRCA1/2* pathogenic variants. Among the predictors for genetic counseling referral are the diagnosis of BC before the age of 50 (60 for triple-negative BC), one sole case of OC, male BC, known family history of BC, OC and/or pancreatic cancer on the same side of the family and others [8].

Outcomes from commercial and academic clinical sequencing-based genetic testing typically range from findings of a known pathogenic variant, a variant of Uncertain Clinical Significance (VUS), no changes (from reference sequence), or a known non-pathogenic (benign) variant organized in a five-tier system (see Figure 1 for a sample of commercial testing results) [9]. Detection of a pathogenic variant in the proband's *BRCA1* gene will prompt specific clinical responses. Clinicians may act by adjusting health recommendations to their at-risk patients and family members, as well as altering their patients' cancer surveillance and treatment. In addition, the identification of an individual carrying a non-pathogenic variant or reference sequence in a family linked to a pathogenic variant in *BRCA1* is also a benefit of genetic testing. Because acting on clinical recommendations tailored for carriers of pathogenic variants may substantially alter outcomes, robust and accurate methods of classification of variants are critical. We identify annotation/classification as a rate-limiting step for the implementation of precision medicine in breast and ovarian cancer care, and review current approaches to eliminate this bottleneck.

IARC	Myriad	Ambry Genetics	GeneDx	Invitae
<b>Class 5 (Definitely pathogenic)</b> >0.99 probability of being pathogenic	<b>Deleterious</b> Associated with a significantly increased cancer risk	<b>Pathogenic Mutation</b> Alterations with sufficient evidence to classify as pathogenic (capable of causing disease).		
<b>Class 4 (Likely pathogenic)</b> 0.95 - 0.99 probability of being pathogenic	<b>Suspected Deleterious</b> Available evidence strongly suggests association with significantly increased cancer risk	<b>Variant, Likely Pathogenic</b> Alterations with strong evidence in favor of pathogenicity.		
<b>Class 3 (Uncertain)</b> 0.05 - 0.0949 probability of being pathogenic	<b>Variant of Uncertain Significance</b> There is not enough information at this time to support a more definitive classification of this sequence change.			
<b>Class 2 (Likely not pathogenic)</b> 0.001 - 0.049 probability of being pathogenic	<b>Favor Polymorphism</b> Evidence strongly indicates the variant is harmless and not associated with an increased cancer risk.	<b>Variant, Likely Benign</b> Alterations with strong evidence against pathogenicity		
<b>Class 1 (Not pathogenic)</b> <0.001 probability of being pathogenic	<b>Polymorphism</b> Harmless, not associated with an increased cancer risk	<b>Benign</b> Alterations with very strong evidence against pathogenicity.		

**Figure 1.** Variations of the five-tier system used to convey information about a variant in *BRCA1*. Classification recommended by the IARC Unclassified Genetic Variants Working Group (IARC) and endorsed by the ENIGMA (Evidence-based Network for the Interpretation of Germline Mutant Alleles) Consortium, and reported by select commercial testing companies in the U.S.

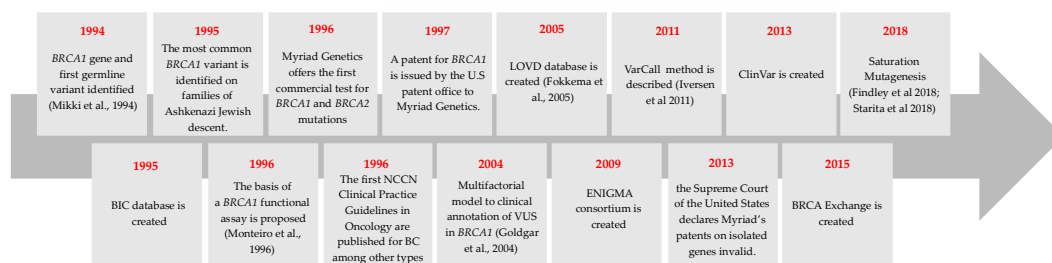
## 2. *BRCA1* variant detection: from first variants to new trends

### 2.1. Detection of the first germline variants in *BRCA1*

The first germline pathogenic variants in *BRCA1* were identified in 1994 (Figure 2), when Miki et al. analyzed sequences from patients' complementary DNA (cDNA) clones, hybrid-selected sequences, and amplified polymerase chain reaction (PCR) products [10]. The combination of these methods allowed the construction of a composite, full-length *BRCA1* cDNA. The four variant alleles were an 11-base pair (bp) deletion in exon 2 (p.Cys24Serfs\*13), a nonsense variant in coding exon 11

(p.Gln1313\*), a single nucleotide insertion in coding exon 20 (p.Gln1756fs), and a missense variant in coding exon 21 (p.Met1775Arg). Since then, more than 3000 unique germline variants have been detected in *BRCA1* (BRCA Exchange; <https://brcaexchange.org/>) [11].

Initially, the *BRCA1* locus region was shown to be lost in sporadic cases of breast and ovarian cancers, prompting the investigation of a putative role of *BRCA1* as a driver gene in sporadic cases of BC and OC [12-15]. However, inactivating somatic mutations in *BRCA1* were shown to be present in a small number of breast (1.6%) and ovarian (3.5%) tumors unselected for family history [16].



**Figure 2. BRCA1 timeline.** BRCA1-related events in the last three decades. Depicted events are discussed throughout this review.

## 2.2. Commercial testing

In the mid-90s, Myriad Genetics, Inc. was awarded a patent for *BRCA1* and *BRCA2* genetic testing by the U.S. Patent Office (Figure 1). In a few years, demand for genetic testing for HBOC increased significantly, and by 2002 hereditary cancers had surpassed all pediatric conditions combined in demand for genetic counselling time in Ontario [17]. Myriad held the patent for approximately 13 years until the American Civil Liberties Union (ACLU), the Association for Molecular Pathology (AMP) and the American College of Medical Genetics (ACMG) challenged its legality and constitutionality. After four years of litigation (from May 2009 to June 2013), the Supreme Court of the United States decided that isolated genomic DNA is not patent-eligible as it was considered a product of nature, however the cDNA which is synthesized in the laboratory is patent-eligible [18,19]. The decision paved the way for other companies to offer genetic testing for *BRCA1/2*.

With the advances in variant detection technologies, the use of Direct-to-Consumer (DTC) genetic testing has increased, creating a new niche in personalized medicine. In March 2018, U.S. Food and Drug Administration authorized the use of DTC testing for the three most common Ashkenazi Jewish mutations in *BRCA1* and *BRCA2* genes [20]. Individuals interested in this three-site panel test can purchase a saliva-based kit from a commercial company, such as 23andme, which makes the result available directly to the consumer. The availability of DTC genetic testing has potential benefits as it may increase awareness and allow easier access to testing which can lead to early identification of individuals at risk. However, the problems may arise during the interpretation of the results with significant implications for intervention (*i.e.* lifestyle change, prophylactic surgery, and chemoprevention) in consumers who receive DTC genetic information, in the absence of adequate genetic counseling. There is a risk of anxiety and distress for individuals receiving test results without understanding its implications. They may also make incorrect clinical decisions based on results they receive from DTC vendors. Importantly, DTC testing may also provide a false guarantee to consumers who receive negative results. Some consumers may be unaware that the absence of those three pathogenic variants does not eliminate the possibility that risk of BC is accounted for by other alleles (pathogenic variants in other positions, genes, or non-coding regions).

Another trend encompassing not only personalized medicine, but also public health, is aimed at improving the HBOC detection rates by screening all women regardless of family history status. This new trend, also known as population-based *BRCA* testing, has been proposed [21]. Among general cancer-free population, family history of HBOC has remained the major factor for referral to genetic testing, even though approximately half of the carriers of *BRCA* pathogenic variants does not have a significant family history [21].

### 2.3. Genetic testing developments

Sanger sequencing of a series of amplicons covering exons and intron-exon borders was initially the preferred method of academic and commercial testing for *BRCA1* and *BRCA2* as it provided fast and accurate results [22-24]. Adoption of massively parallel sequencing allowed for cost-efficient screening of multiple gene panels, exomes, and genomes. More comprehensive testing, involving a large set of genes, is clinically beneficial to patients who are suspected of having HBOC syndrome, but may not be linked to *BRCA1* or *BRCA2*. However, the likelihood of receiving a VUS result is considerably higher because the clinical impact of many rare variants typically cannot be determined and because for several genes their association with disease have not yet been firmly established.

However, amplicon-based Sanger sequencing or short-read lengths from massively parallel sequencing do not reliably detect large genomic rearrangements (LGR). LGR have been identified in multiple HBOC families and are estimated to be responsible for 5-10% of all *BRCA1/2* pathogenic variants [25]. *BRCA1* gene is an *Alu*-enriched genomic region, representing more than 40% of its intronic sequence and this recombinogenic feature has been proposed to underlie the relatively high *BRCA1* LGR frequency in HBOC families [26]. However, different studies point to large differences in prevalence of *BRCA1* rearrangements across different populations. LRG ranges from very rare among Canadian and Finish families [27,28] to more than one-third of pathogenic alterations among families in northern Italy [29]. The multiplex ligation-dependent probe amplification (MLPA) is the most commonly used method for the identification of these alterations [30].

### 2.4. The spectrum of *BRCA1* variants across the world

Knowledge of the prevalence of *BRCA1* pathogenic variants across different populations is important for planning cost-effective preventive interventions and for the design of low-cost testing panels in developing countries. The estimated prevalence of *BRCA1* pathogenic variants in an unselected population is better characterized in non-Hispanic whites from the United States, United Kingdom and Canada (carrier frequency ranging from 0.1 to 0.3%) than in other ethnic groups [31,32]. According to the Exome Variant Server for the NHLBI GO Exome Sequencing Project (n = 2,203 African-Americans and 4,300 European-Americans; <http://evs.gs.washington.edu/EVS/>), the frequency of *BRCA1* pathogenic variants in an unselected population is 0.65% and 0.51% in European and African Americans, respectively. Further, data derived from the Exome Aggregation Consortium (ExAC; n = 60,706; <http://exac.broadinstitute.org/>) indicates that frequencies for *BRCA1* pathogenic variants vary among African (0.00%), Latino (0.04%), East Asian (0.1%) and South Asian (0.2%). When it comes to individuals with Ashkenazi ancestry, the prevalence rises to 1.2% [32-35]. These studies may underestimate the prevalence of *BRCA1* pathogenic variants in the general population as they do not include large genomic rearrangements or VUS.

Among BC patients unselected for family cancer history, the prevalence of *BRCA1* pathogenic variants varies from 0.5% to 3.1% in whites from United States, United Kingdom and Australia. Asian-Americans have a frequency of 0.5%, while Asian populations (including Chinese, Japanese, Philippines, Pakistanis and Korean individuals) present a prevalence ranging from 0.8% to 3.9%. Additionally, African-Americans and Hispanic-Americans present a frequency of 1.4% and 3.5%, respectively [36].

The prevalence of *BRCA1* pathogenic variants is much higher in particular groups that share a common ancestor which carried a founder mutation. The best characterized *BRCA1* founder pathogenic variants are c.5163\_5164insC (a.k.a. 5282insC) and c.68\_69delAG (a.k.a. 185delAG) found Ashkenazi Jewish individuals in the U.S., but other distinct founder pathogenic variants have been found in French Canadians (c.4327C>T; a.k.a. 4446C>T), Central Eastern Europeans (c.181T>G; a.k.a. 300T>G; c.4043delG; a.k.a. 4162delG), Mexicans (ex9-12del), Brazilians (c.5266dupC; a.k.a. 5382insC) and Colombians (c.3331\_3334delCAAG; a.k.a. c.3450\_3453delCAAG; and p.Ala1708Glu) [37-42].

The identification of founder mutations in ethnic groups or specific populations can facilitate ancestry-informed genetic test and enable cost-effective genetic screenings. It has been proposed that the Ashkenazi Jewish population in the U.S. and U.K. would be a starting point for the implementation of a population-based screening for *BRCA1* and *BRCA2* [43] [44] [45] [21]. In that specific population, both *BRCA1* (c.5163\_5164insC and c.68\_69delAG) and *BRCA2* (c.5946delT; a.k.a. 6174delT) founder mutations account for 90% of all pathogenic variants [44]. A cost-effective approach was developed to help identify recurrent pathogenic variants in Hispanic/Latino populations [41].

### 3. *BRCA1* variant annotation and classification

#### 3.1. Definitions

For the purposes of this review we make a distinction between annotation, the process of adding evidence from multiple sources to a variant, and classification. Importantly, a variant may be heavily annotated and yet remain unclassified according to its pathogenicity. Here we define classification as the process of assigning a variant to one of the IARC Classes either through a rule-base (e.g. variants whose impact on function can be inferred from the genetic code) or a multifactorial statistical model. Annotated variants that are assessed by the multifactorial model but do not reach statistical thresholds for classification as benign (Class 1), likely benign (Class 2), likely pathogenic (Class 4) or pathogenic (Class 5) remain as Class 3 (still uncertain) (Figure 1).

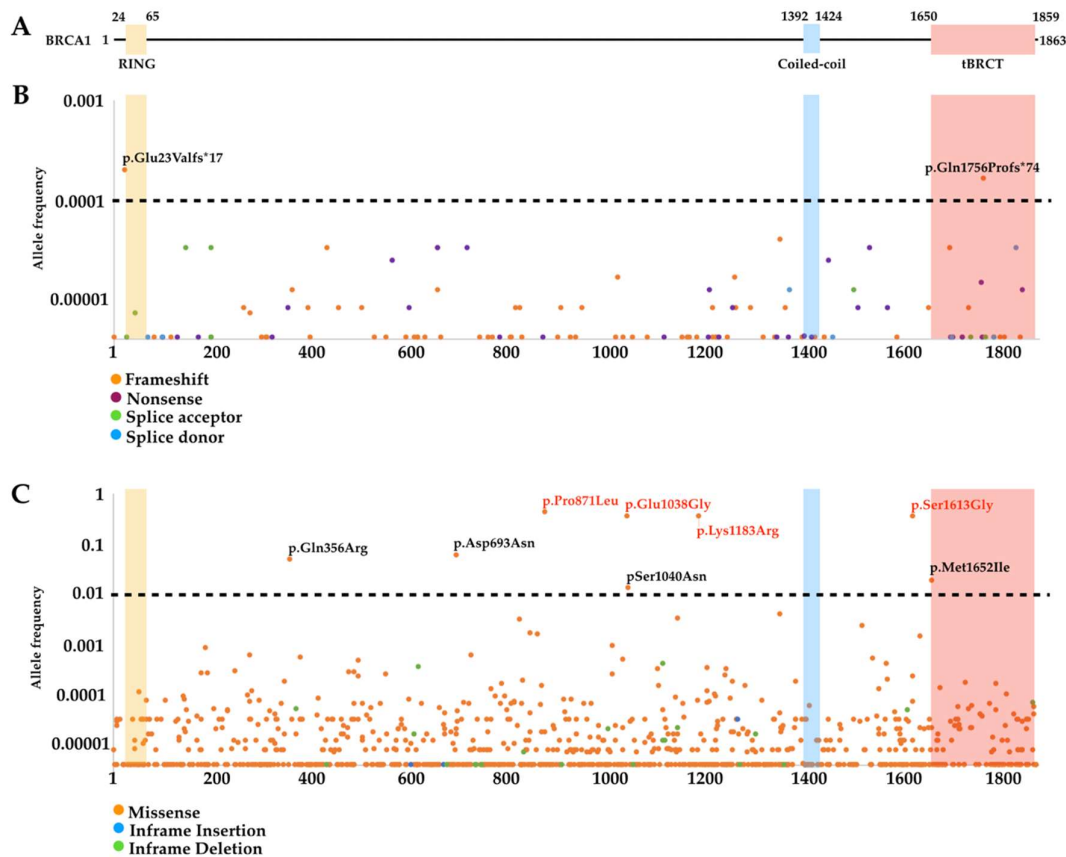
#### 3.2. Mutational landscape

Pathogenic variants, including nonsense and frameshift changes, in *BRCA1* are scattered along its sequence without a specific hotspot (Figure 3). Alterations in the coding region can generate several different outcomes on the protein product which, in some cases, can be used to infer a functional impact [46]. Because loss-of-function variants of *BRCA1* are associated with significantly increase risk of cancer, frameshift and nonsense mutations (Figure 3A), whose impact on the protein can be easily inferred from the genetic code, are classified as pathogenic alterations [46]. Nonsense variants (Figure 3A) are characterized by the introduction of a premature stop codon. Frameshift occurs when the insertion or deletion of nucleotides disrupt the original reading frame. Usually, this alteration also leads to a premature stop codon. Because the nonsense variant p.Tyr1853\*, which leads to the loss of the last 11 amino acid residues in *BRCA1*, is associated with increased risk, any premature stop codon upstream of this codon (generated by a nonsense or frameshift mutations) is likely to constitute a pathogenic variant [47-50]. The same interpretation can be made toward alterations on acceptor or donor splice sites, which are usually classified as pathogenic due to the predicted truncation of the full-length protein

As shown in Figure 3A, frameshift variants are more frequent than nonsense and splice site alterations. According to Genome Aggregation Database (gnomAD; n = 125,748 exome and 15,708 whole-genome sequences; <https://gnomad.broadinstitute.org/>), the highest allele frequencies observed for p.Glu23Valfs\*17 (0.0001987) and p.Gln1756Profs\*74 (0.0001623) variants. Nonsense alleles are rarer, with the most common p.Lys654T\* and p.Ser713\* showing a frequency of 0.0000323 [51]. The functional interpretation of missense and small inframe insertions/deletions offer a more challenging scenario (Figure 3B). The exact impact of a single amino acid residue change or inframe insertion/deletion of small regions in the biochemical and biophysical properties of the protein is



difficult to predict. Missense variants are the most frequent type of *BRCA1* germline alterations (Figure 2B). Some of these variants occur with an allele frequency >1% and are therefore considered non-pathogenic or benign (e.g. p.Gln356Arg, p.Asp693Asn, p.Pro871Leu, p.Glu1038Gly, p.Ser1040Asn, p.Lys1183Arg, p.Ser1613Gly and p.Met1652Ile) [51]. On the other hand, the vast majority of *BRCA1* missense variants have low allele frequencies (<1%). Inframe insertions/deletions are the least frequent class of variants (<0.001) [51]. The use of whole-genome sequencing for screening of individuals suspected of being carriers, which has led to the findings of VUS in non-coding regions has raised a new challenge for annotation and classification. For intronic and untranslated regions, gnomAD now includes approximately a thousand of VUS.



**Figure 3. *BRCA1* allele frequency.** Graphic representation of the allele frequency of *BRCA1* (Ensembl transcript ENST00000357654.7) germline variants (HGVS nomenclature) deposited on the genome aggregation database (gnomAD) with data for individuals not selected family or personal history of cancer [51]. (A) Frameshift (orange), nonsense (purple), splice acceptor (green) and donors (blue) mutations. (B) Missense (orange), inframe insertion (blue) and deletion (green). The RING-finger, coiled-coil and tBRCT domains are represented by the yellow, blue and pink backgrounds respectively.

### 3.2. Variants of Uncertain Significance (VUS)

Variants whose impact on function cannot be directly inferred by the genetic code are categorized as VUS and are evaluated by multifactorial likelihood models that use personal and family history of cancer, segregation data, prediction tools, and co-occurrence with a pathogenic *BRCA1* variant [52-54]. VUS are primarily missense and splicing variants. However, the low frequency of the majority of germline missense variants in the population (<1/10,000; Figure 3B) impairs clinical annotation derived from linkage analysis. The limited access to family history and genetic information impedes the use of likelihood models. The current challenge of clinical

annotation of VUS lies on the inability to assess the pathogenicity of a variant without family or epidemiological data. In this context, the role of functional data to support VUS classification has become critical.

### 3.3 Functional assays

Functional assays represent an important tool for assessing the impact of a single amino acid residue change on a specific function or the integrity of a specific protein functional domain. *BRCA1* encodes a homonymous protein composed by 1863 amino acid residues that comprises a RING-finger domain at the amino-terminus, a coiled-coil motif at the central region and two BRCT domains in tandem (tBRCT) on its carboxy-terminus (Figure 3). *BRCA1* acts as a scaffold for the recruitment of several other proteins associated with genomic integrity maintenance, such as cell cycle control, DNA damage repair and transcriptional regulation [55].

Throughout the years, several functional assays have been proposed to evaluate the impact of variants on *BRCA1* biological roles and biochemical properties (E3 ubiquitin ligase activity, cell cycle control, genotoxic agent sensibility, phosphopeptide binding, protease sensitivity and others)[56]. For variants in the carboxy-terminus of *BRCA1* all assays display high specificity (80-100%) but more variable sensitivity (63-100%) with lower sensitivity seen in yeast-based presumably due to pathogenic variants which are stable at lower temperatures [57]. The high sensitivity and specificity found for most mammalian-based assays allow for the use of functional data in classifying VUS.

The first proposed functional assay for *BRCA1* was based on the observation that the tBRCT domain integrity correlates to the transactivation activity (TA) of its C-terminal region [49]. The assay was further validated by the functional impact of known cancer-associated variants and *BRCA1* TA. Over the last 15 years, more than 300 variants enclosed within the 1396–1863 amino acid residues (all known missense variants in the C-terminal region of the *BRCA1*) were evaluated [57,58]. By comparing the results of *BRCA1* TA with a reference panel of 49 missense variants classified by multifactorial models, using a Bayesian hierarchical model (VarCall) to predict the likelihood of pathogenicity, we observed a 1.0 sensitivity and 1.0 specificity (lower bound of 95% confidence interval = 0.78 and 0.84, respectively), demonstrating that this approach can classify VUS with confidence [57].

Recently, two saturation mutagenesis-based high-throughput approaches evaluated the impact of 1,056 and 3,893 *BRCA1* variants in exons 2-7 and 15-24, respectively [59,60]. Each study used a distinct biological role of *BRCA1*. Starita and colleagues [61] interrogated the impact of alteration on the amino-terminus of *BRCA1* on its role on Homology-directed Repair (HDR) while Findlay and colleagues [59] based their assay on the requirement of a functional *BRCA1* for viability in a near-haploid human cell line (HAP1). These studies demonstrated the feasibility of this approach and reported an excellent agreement with the available clinical data in ClinVar database [59]. The high sensitivity and specificity found for most mammalian-based assays allow for the use of functional data in classifying VUS.

## 4. *BRCA1* Variant Databases and Information Dissemination

An important factor in implementing precision medicine approaches for BC and OC is the availability of freely-accessible and accurate information on variants. Databases that contain information on *BRCA1* variants come in several forms. For example several databases that aggregate information from exome or genome sequencing in populations unselected for personal or family history can be used to estimate the frequency of variants in diverse populations. They include the Exome Variant Viewer from the Exome Sequencing Project (<http://evs.gs.washington.edu/EVS/>), the Exome Aggregation Consortium (ExAC; <http://exac.broadinstitute.org/>) and the Genome Aggregation database (<https://gnomad.broadinstitute.org/>). However, these databases do not contain variant classification, although some may provide in silico prediction tools to predict the potential impact of the variant on the function of the protein.

Some databases aggregate data from clinical testing, in which most individuals tested have a personal or family history of disease, or are suspected of being carriers of a predisposition gene. ClinVar (<https://www.ncbi.nlm.nih.gov/clinvar/>) is the most widely used clinical database and aggregates information about genomic variation in any gene and its relationship to human disease. It displays variant classifications suggested by the depositor as well as those curated by expert panels.

There are several databases that are specific for *BRCA1* and *BRCA2*. The Breast Cancer Information Core database (BIC; <https://research.nhgri.nih.gov/bic/>) was the first centralized database for protocols, primers, and variants found in *BRCA1/2* during genetic testing [62-64]. Importantly, frequency of variants in this database should not be taken as an indication of allele frequency in the general population because most individuals tested were selected for family or personal history. The BIC database contains information about pathogenicity, as contributed by the data depositor and as of lately, as curated by the ENIGMA consortium. The BRCA1 Circos interactive tool (<https://research.nhgri.nih.gov/bic/circos/>) is available through the BIC (NHGRI) webpage and compiles functional data for missense variants in BRCA1 [56]. Information about VUS that have recently been classified by the multifactorial statistical model [54,65] can be found in the Ex-VUS LOVD database (<http://hci-exlovd.hci.utah.edu/home.php>), and a compilation of scientific literature referring to *BRCA1/2* variants is available in Global Variome shared database ([https://databases.lovd.nl/shared/variants/BRCA1?search\\_VariantOnGenome/Genetic\\_origin=vitro](https://databases.lovd.nl/shared/variants/BRCA1?search_VariantOnGenome/Genetic_origin=vitro)) also in LOVD format.

The BIC database is currently phasing out as all its variant information has been transferred to BRCA Exchange (<https://brcaexchange.org/>). BRCA Exchange, is part of the BRCA Challenge, a data-sharing initiative by the Global Alliance for Genomics and Health (GA4GH) and aggregates *BRCA1* and *BRCA2* data on the impact of genetic variation on cancer risk. It contains over 20,000 variants with over 6,000 with expert classifications based on shared information from existing clinical and population databases discussed above (BIC, ClinVar, LOVD, gnomAD, etc.). Importantly, the BRCA Exchange database is now available through a phone app. BRCA Exchange is a significant step towards wide dissemination of accurate information on *BRCA1* variants.

## 5. Conclusions

Since the identification of *BRCA1* in 1994, the screening of germline pathogenic variants that might increase an individual's risk of BC and OC has become main stream in clinical practice. The advances in DNA sequencing has enable rapid, accurate, and cost-effective detection of variants in *BRCA1*. Rapid development has also occurred in the dissemination of information on variants with the recent deployment of BRCA Exchange. However, the main challenge for the use of this data to improve outcomes is the classification of variants according to their clinical relevance, in particular rare variants for which population and clinical information is lacking. Validated functional assays hold the promise to accelerate the classification of these problematic variants.

**Acknowledgments:** Work in the Monteiro Lab is funded by NIH/NCI award CA116167. T.C.N. is a Fulbright Scholar.

**Author Contributions:** All authors were involved in design, data curation, writing, preparing illustrations, reviewing and editing the manuscript.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Siegel, R.L.; Miller, K.D.; Jemal, A., Cancer statistics, 2018. *CA: a cancer journal for clinicians* **2018**, *68*, 7-30.
2. Bray, F.; Ferlay, J.; Soerjomataram, I.; Siegel, R.L.; Torre, L.A.; Jemal, A., Global cancer statistics 2018: Globocan estimates of incidence and mortality worldwide for 36 cancers in 185 countries. *CA: a cancer journal for clinicians* **2018**, *68*, 394-424.



3. Brinton, L.A.G., M.M.; Gierach, G.L.; Breast cancer. In *Cancer epidemiology and prevention*, 4th edition ed.; Thun, M.L., M.S.; Cerhan, J.R.; Haiman, C.A.; Schottenfeld, D., Ed. Oxford University Press: New York, 2018.
4. Torre, L.A.; Trabert, B.; DeSantis, C.E.; Miller, K.D.; Samimi, G.; Runowicz, C.D.; Gaudet, M.M.; Jemal, A.; Siegel, R.L., Ovarian cancer statistics, 2018. *CA: a cancer journal for clinicians* **2018**.
5. Fackenthal, J.D.; Olopade, O.I., Breast cancer risk associated with brca1 and brca2 in diverse populations. *Nature reviews. Cancer* **2007**, *7*, 937-948.
6. Alsop, K.; Fereday, S.; Meldrum, C.; deFazio, A.; Emmanuel, C.; George, J.; Dobrovic, A.; Birrer, M.J.; Webb, P.M.; Stewart, C., *et al.*, Brca mutation frequency and patterns of treatment response in brca mutation-positive women with ovarian cancer: A report from the Australian ovarian cancer study group. *Journal of clinical oncology : official journal of the American Society of Clinical Oncology* **2012**, *30*, 2654-2663.
7. Kuchenbaecker, K.B.; Hopper, J.L.; Barnes, D.R.; Phillips, K.A.; Mooij, T.M.; Roos-Blom, M.J.; Jervis, S.; van Leeuwen, F.E.; Milne, R.L.; Andrieu, N., *et al.*, Risks of breast, ovarian, and contralateral breast cancer for brca1 and brca2 mutation carriers. *JAMA* **2017**, *317*, 2402-2416.
8. Network, N.C.C. Genetic/familial high-risk assessment: Breast and ovarian (version 3.2019). [https://www.nccn.org/professionals/physician\\_gls/pdf/genetics\\_screening.pdf](https://www.nccn.org/professionals/physician_gls/pdf/genetics_screening.pdf)
9. Plon, S.E.; Eccles, D.M.; Easton, D.; Foulkes, W.D.; Genuardi, M.; Greenblatt, M.S.; Hogervorst, F.B.; Hoogerbrugge, N.; Spurdle, A.B.; Tavtigian, S.V., Sequence variant classification and reporting: Recommendations for improving the interpretation of cancer susceptibility genetic test results. *Human mutation* **2008**, *29*, 1282-1291.
10. Miki, Y.; Swensen, J.; Shattuck-Eidens, D.; Futreal, P.A.; Harshman, K.; Tavtigian, S.; Liu, Q.; Cochran, C.; Bennett, L.M.; Ding, W., A strong candidate for the breast and ovarian cancer susceptibility gene brca1. *Science* **1994**, *266*, 66-71.
11. Cline, M.S.; Liao, R.G.; Parsons, M.T.; Paten, B.; Alquaddoomi, F.; Antoniou, A.; Baxter, S.; Brody, L.; Cook-Deegan, R.; Coffin, A., *et al.*, Brca challenge: Brca exchange as a global resource for variants in brca1 and brca2. *PLoS genetics* **2018**, *14*, e1007752.
12. Futreal, P.A.; Liu, Q.; Shattuck-Eidens, D.; Cochran, C.; Harshman, K.; Tavtigian, S.; Bennett, L.M.; Haugen-Strano, A.; Swensen, J.; Miki, Y., Brca1 mutations in primary breast and ovarian carcinomas. *Science* **1994**, *266*, 120-122.
13. Takahashi, H.; Behbakht, K.; McGovern, P.E.; Chiu, H.C.; Couch, F.J.; Weber, B.L.; Friedman, L.S.; King, M.C.; Furusato, M.; LiVolsi, V.A., Mutation analysis of the brca1 gene in ovarian cancers. *Cancer research* **1995**, *55*, 2998-3002.
14. Merajver, S.D.; Pham, T.M.; Caduff, R.F.; Chen, M.; Poy, E.L.; Cooney, K.A.; Weber, B.L.; Collins, F.S.; Johnston, C.; Frank, T.S., Somatic mutations in the brca1 gene in sporadic ovarian tumours. *Nature genetics* **1995**, *9*, 439-443.
15. Hosking, L.; Trowsdale, J.; Nicolai, H.; Solomon, E.; Foulkes, W.; Stamp, G.; Signer, E.; Jeffreys, A., A somatic brca1 mutation in an ovarian tumour. *Nature genetics* **1995**, *9*, 343-344.
16. Kandoth, C.; McLellan, M.D.; Vandin, F.; Ye, K.; Niu, B.; Lu, C.; Xie, M.; Zhang, Q.; McMichael, J.F.; Wyczalkowski, M.A., *et al.*, Mutational landscape and significance across 12 major cancer types. *Nature* **2013**, *502*, 333-339.
17. Andermann, A.; Narod, S.A., Genetic counselling for familial breast and ovarian cancer in Ontario. *Journal of medical genetics* **2002**, *39*, 695-696.

18. Association for molecular pathology v. Myriad genetics, inc. States, S.C.o.t.U., Ed. 2013; Vol. 569 U. S. 576.
19. Kesselheim, A.S.; Cook-Deegan, R.M.; Winickoff, D.E.; Mello, M.M., Gene patenting--the supreme court finally speaks. *The New England journal of medicine* **2013**, *369*, 869-875.
20. Genetic health risk assessment system. Administration, F.D., Ed. Code of Federal Regulations, 2018; Vol. 21CFR866.5950.
21. Gabai-Kapara, E.; Lahad, A.; Kaufman, B.; Friedman, E.; Segev, S.; Renbaum, P.; Beeri, R.; Gal, M.; Grinshpun-Cohen, J.; Djemal, K., *et al.*, Population-based screening for breast and ovarian cancer risk due to brca1 and brca2. *Proceedings of the National Academy of Sciences of the United States of America* **2014**, *111*, 14205-14210.
22. Frank, T.S.; Deffenbaugh, A.M.; Reid, J.E.; Hulick, M.; Ward, B.E.; Lingenfelter, B.; Gumpfer, K.L.; Scholl, T.; Tavtigian, S.V.; Pruss, D.R., *et al.*, Clinical characteristics of individuals with germline mutations in brca1 and brca2: Analysis of 10,000 individuals. *Journal of Clinical Oncology* **2002**, *20*, 1480-1490.
23. Frank, T.S.; Manley, S.A.; Olopade, O.I.; Cummings, S.; Garber, J.E.; Bernhardt, B.; Antman, K.; Russo, D.; Wood, M.E.; Mullineau, L., *et al.*, Sequence analysis of brca1 and brca2: Correlation of mutations with family history and ovarian cancer risk. *Journal of clinical oncology : official journal of the American Society of Clinical Oncology* **1998**, *16*, 2417-2425.
24. Serova-Sinilnikova, O.M.; Boutrand, L.; Stoppa-Lyonnet, D.; Bressac-de-Paillerets, B.; Dubois, V.; Lasset, C.; Janin, N.; Bignon, Y.J.; Longy, M.; Maugard, C., *et al.*, Brca2 mutations in hereditary breast and ovarian cancer in france. *Am.J Hum.Genet* **1997**, *60*, 1236-1239.
25. del Valle, J.; Feliubadalo, L.; Nadal, M.; Teule, A.; Miro, R.; Cuesta, R.; Tornero, E.; Menendez, M.; Darder, E.; Brunet, J., *et al.*, Identification and comprehensive characterization of large genomic rearrangements in the brca1 and brca2 genes. *Breast cancer research and treatment* **2010**, *122*, 733-743.
26. Smith, T.M.; Lee, M.K.; Szabo, C.I.; Jerome, N.; McEuen, M.; Taylor, M.; Hood, L.; King, M.C., Complete genomic sequence and analysis of 117 kb of human DNA containing the gene brca1. *Genome research* **1996**, *6*, 1029-1049.
27. Moisan, A.M.; Fortin, J.; Dumont, M.; Samson, C.; Bessette, P.; Chiquette, J.; Laframboise, R.; Lepine, J.; Lesperance, B.; Pichette, R., *et al.*, No evidence of brca1/2 genomic rearrangements in high-risk french-canadian breast/ovarian cancer families. *Genet Test* **2006**, *10*, 104-115.
28. Lahti-Domenici, J.; Rapakko, K.; Paakkonen, K.; Allinen, M.; Nevanlinna, H.; Kujala, M.; Huusko, P.; Winqvist, R., Exclusion of large deletions and other rearrangements in brca1 and brca2 in finnish breast and ovarian cancer families. *Cancer genetics and cytogenetics* **2001**, *129*, 120-123.
29. Montagna, M.; Dalla Palma, M.; Menin, C.; Agata, S.; De Nicolo, A.; Chieco-Bianchi, L.; D'Andrea, E., Genomic rearrangements account for more than one-third of the brca1 mutations in northern italian breast/ovarian cancer families. *Human molecular genetics* **2003**, *12*, 1055-1061.
30. Toland, A.E.; Forman, A.; Couch, F.J.; Culver, J.O.; Eccles, D.M.; Foulkes, W.D.; Hogervorst, F.B.L.; Houdayer, C.; Levy-Lahad, E.; Monteiro, A.N., *et al.*, Clinical testing of brca1 and brca2: A worldwide snapshot of technological practices. *NPJ Genom Med* **2018**, *3*, 7.
31. Risch, H.A.; McLaughlin, J.R.; Cole, D.E.; Rosen, B.; Bradley, L.; Fan, I.; Tang, J.; Li, S.; Zhang, S.; Shaw, P.A., *et al.*, Population brca1 and brca2 mutation frequencies and cancer penetrances: A kin-cohort study in ontario, canada. *J Natl.Cancer Inst.* **2006**, *98*, 1694-1706.

32. Whittemore, A.S.; Gong, G.; John, E.M.; McGuire, V.; Li, F.P.; Ostrow, K.L.; Dicioccio, R.; Felberg, A.; West, D.W., Prevalence of brca1 mutation carriers among u.S. Non-hispanic whites. *Cancer Epidemiol Biomarkers Prev* **2004**, *13*, 2078-2083.
33. Rebbeck, T.R.; Friebel, T.M.; Friedman, E.; Hamann, U.; Huo, D.; Kwong, A.; Olah, E.; Olopade, O.I.; Solano, A.R.; Teo, S.H., *et al.*, Mutational spectrum in a worldwide study of 29,700 families with brca1 or brca2 mutations. *Hum Mutat* **2018**, *39*, 593-620.
34. Struewing, J.P.; Hartge, P.; Wacholder, S.; Baker, S.M.; Berlin, M.; McAdams, M.; Timmerman, M.M.; Brody, L.C.; Tucker, M.A., The risk of cancer associated with specific mutations of brca1 and brca2 among ashkenazi jews. *N Engl J Med* **1997**, *336*, 1401-1408.
35. Peto, J.; Collins, N.; Barfoot, R.; Seal, S.; Warren, W.; Rahman, N.; Easton, D.F.; Evans, C.; Deacon, J.; Stratton, M.R., Prevalence of brca1 and brca2 gene mutations in patients with early-onset breast cancer. *J Natl Cancer Inst* **1999**, *91*, 943-949.
36. Kurian, A.W., Brca1 and brca2 mutations across race and ethnicity: Distribution and clinical implications. *Current opinion in obstetrics & gynecology* **2010**, *22*, 72-78.
37. Oros, K.K.; Ghadirian, P.; Maugard, C.M.; Perret, C.; Paredes, Y.; Mes-Masson, A.M.; Foulkes, W.D.; Provencher, D.; Tonin, P.N., Application of brca1 and brca2 mutation carrier prediction models in breast and/or ovarian cancer families of french canadian descent. *Clin Genet* **2006**, *70*, 320-329.
38. Tonin, P.; Weber, B.; Offit, K.; Couch, F.; Rebbeck, T.R.; Neuhausen, S.; Godwin, A.K.; Daly, M.; Wagner-Costalos, J.; Berman, D., *et al.*, Frequency of recurrent brca1 and brca2 mutations in ashkenazi jewish breast cancer families. *Nat Med* **1996**, *2*, 1179-1183.
39. Tonin, P.N.; Perret, C.; Lambert, J.A.; Paradis, A.J.; Kantemiroff, T.; Benoit, M.H.; Martin, G.; Foulkes, W.D.; Ghadirian, P., Founder brca1 and brca2 mutations in early-onset french canadian breast cancer cases unselected for family history. *Int J Cancer* **2001**, *95*, 189-193.
40. Gorski, B.; Byrski, T.; Huzarski, T.; Jakubowska, A.; Menkiszak, J.; Gronwald, J.; Pluzanska, A.; Bebenek, M.; Fischer-Maliszewska, L.; Grzybowska, E., *et al.*, Founder mutations in the brca1 gene in polish families with breast-ovarian cancer. *Am J Hum Genet* **2000**, *66*, 1963-1968.
41. Villarreal-Garza, C.; Weitzel, J.N.; Llacuachaqui, M.; Sifuentes, E.; Magallanes-Hoyos, M.C.; Gallardo, L.; Alvarez-Gomez, R.M.; Herzog, J.; Castillo, D.; Royer, R., *et al.*, The prevalence of brca1 and brca2 mutations among young mexican women with triple-negative breast cancer. *Breast Cancer Res Treat* **2015**, *150*, 389-394.
42. Ossa, C.A.; Torres, D., Founder and recurrent mutations in brca1 and brca2 genes in latin american countries: State of the art and literature review. *Oncologist* **2016**, *21*, 832-839.
43. Manchanda, R.; Patel, S.; Antoniou, A.C.; Levy-Lahad, E.; Turnbull, C.; Evans, D.G.; Hopper, J.L.; Macinnis, R.J.; Menon, U.; Jacobs, I., *et al.*, Cost-effectiveness of population based brca testing with varying ashkenazi jewish ancestry. *Am J Obstet Gynecol* **2017**, *217*, 578 e571-578 e512.
44. Lynce, F.; Isaacs, C., Population-based brca1/2 testing in ashkenazi jews: Ready for prime time. *J Natl Compr Canc Netw* **2016**, *14*, 809-812.
45. King, M.C.; Levy-Lahad, E.; Lahad, A., Population-based screening for brca1 and brca2: 2014 lasker award. *JAMA* **2014**, *312*, 1091-1092.
46. Szabo, C.I.; Worley, T.; Monteiro, A.N., Understanding germ-line mutations in brca1. *Cancer Biol Ther.* **2004**, *3*, 515-520.

47. Friedman, L.S.; Ostermeyer, E.A.; Szabo, C.I.; Dowd, P.; Lynch, E.D.; Rowell, S.E.; King, M.C., Confirmation of brca1 by analysis of germline mutations linked to breast and ovarian cancer in ten families. *Nature genetics* **1994**, *8*, 399-404.
48. Gough, C.A.; Gojobori, T.; Imanishi, T., Cancer-related mutations in brca1-brct cause long-range structural changes in protein-protein binding sites: A molecular dynamics study. *Proteins* **2007**, *66*, 69-86.
49. Monteiro, A.N.; August, A.; Hanafusa, H., Evidence for a transcriptional activation function of brca1 c-terminal region. *Proc.Natl.Acad.Sci.U.S.A* **1996**, *93*, 13595-13599.
50. Rodriguez, J.A.; Au, W.W.; Henderson, B.R., Cytoplasmic mislocalization of brca1 caused by cancer-associated mutations in the brct domain. *Exp.Cell Res* **2004**, *293*, 14-21.
51. Lek, M.; Karczewski, K.J.; Minikel, E.V.; Samocha, K.E.; Banks, E.; Fennell, T.; O'Donnell-Luria, A.H.; Ware, J.S.; Hill, A.J.; Cummings, B.B., *et al.*, Analysis of protein-coding genetic variation in 60,706 humans. *Nature* **2016**, *536*, 285-291.
52. Goldgar, D.E.; Easton, D.F.; Deffenbaugh, A.M.; Monteiro, A.N.; Tavtigian, S.V.; Couch, F.J.; Breast Cancer Information Core Steering, C., Integrated evaluation of DNA sequence variants of unknown clinical significance: Application to brca1 and brca2. *Am J Hum Genet* **2004**, *75*, 535-544.
53. Lindor, N.M.; Guidugli, L.; Wang, X.; Vallee, M.P.; Monteiro, A.N.; Tavtigian, S.; Goldgar, D.E.; Couch, F.J., A review of a multifactorial probability-based model for classification of brca1 and brca2 variants of uncertain significance (vus). *Human mutation* **2012**, *33*, 8-21.
54. Easton, D.F.; Deffenbaugh, A.M.; Pruss, D.; Frye, C.; Wenstrup, R.J.; Ien-Brady, K.; Tavtigian, S.V.; Monteiro, A.N.; Iversen, E.S.; Couch, F.J., *et al.*, A systematic genetic assessment of 1,433 sequence variants of unknown clinical significance in the brca1 and brca2 breast cancer-predisposition genes. *Am.J Hum.Genet.* **2007**, *81*, 873-883.
55. Jiang, Q.; Greenberg, R.A., Deciphering the brca1 tumor suppressor network. *J Biol Chem* **2015**, *290*, 17724-17732.
56. Jhuraney, A.; Velkova, A.; Johnson, R.C.; Kessing, B.; Carvalho, R.S.; Whiley, P.; Spurdle, A.B.; Vreeswijk, M.P.; Caputo, S.M.; Millot, G.A., *et al.*, Brca1 circoS: A visualisation resource for functional analysis of missense variants. *Journal of medical genetics* **2015**, *52*, 224-230.
57. Fernandes, V.C.G., V.A.; Di Pietro, G.; Shields, C.; Amankwah, K.; Nepomuceno, T.C.; de Gregoriis, G.; Abreu, R.B.; Harro, C.; Gomes, T.T.; Silva, R.F.; Suarez-Kurtz, G.; Couch, F.J.; Iversen, E.S.; Monteiro, A.N.; Carvalho, M.A., Functional impact of amino acid substitutions at secondary structures in the brct domains of the tumor suppressor brca1 predict clinically relevant missense variants. *Journal of Biological Chemistry* **2019**, *In press*.
58. Woods, N.T.B., R.; Golubeva, V.; Jhuraney, A.; De-Gregoriis, G.; Vlacova, T.; Goldgar, D.E.; Couch, F.J.; Carvalho, M.A.; Iversen, E.S.; Monteiro, A.N., Functional assays provide a robust tool for the clinical annotation of genetic variants of uncertain significance. *NPJ Genomic Medicine* **2016**, *1*, 16001.
59. Findlay, G.M.; Daza, R.M.; Martin, B.; Zhang, M.D.; Leith, A.P.; Gasperini, M.; Janizek, J.D.; Huang, X.; Starita, L.M.; Shendure, J., Accurate classification of brca1 variants with saturation genome editing. *Nature* **2018**, *562*, 217-222.
60. Starita, L.M.; Islam, M.M.; Banerjee, T.; Adamovich, A.I.; Gullingsrud, J.; Fields, S.; Shendure, J.; Parvin, J.D., A multiplex homology-directed DNA repair assay reveals the impact of more than 1,000 brca1 missense substitution variants on protein function. *Am J Hum Genet* **2018**, *103*, 498-508.

61. Starita, L.M.; Islam, M.M.; Banerjee, T.; Adamovich, A.I.; Gullingsrud, J.; Fields, S.; Shendure, J.; Parvin, J.D., A multiplex homology-directed DNA repair assay reveals the impact of more than 1,000 brca1 missense substitution variants on protein function. *American journal of human genetics* **2018**.
62. Szabo, C.; Masiello, A.; Ryan, J.F.; Brody, L.C., The breast cancer information core: Database design, structure, and scope. *Human mutation* **2000**, *16*, 123-131.
63. Friend, S.; Borresen, A.L.; Brody, L.; Casey, G.; Devilee, P.; Gayther, S.; Goldgar, D.; Murphy, P.; Weber, B.L.; Wiseman, R., Breast cancer information on the web. *Nature genetics* **1995**, *11*, 238-239.
64. Toland, A.E.; Brody, L.C.; the, B.I.C.S.C., Lessons learned from two decades of brca1 and brca2 genetic testing: The evolution of data sharing and variant classification. *Genetics in Medicine* **2018**.
65. Goldgar, D.E.; Easton, D.F.; Deffenbaugh, A.M.; Monteiro, A.N.; Tavtigian, S.V.; Couch, F.J., Integrated evaluation of DNA sequence variants of unknown clinical significance: Application to brca1 and brca2. *American journal of human genetics* **2004**, *75*, 535-544.