Fanconi anaemia, BRCA2 mutations and childhood cancer: a developmental perspective from clinical and epidemiological observations with implications for genetic counselling

Stefan Meyer,1,2,3,4,5 Marc Tischkowitz,6 Kate Chandler,4,7,8 Alan Gillespie,9,10 Jillian M Birch,5,11 D Gareth Evans7,8

ABSTRACT
Fanconi anaemia (FA) is an inherited condition characterised by congenital and developmental abnormalities and a strong cancer predisposition. In around 3–5% of cases FA is caused by biallelic mutations in the BRCA2 gene. Individuals heterozygous for BRCA2 mutations have an increased risk of inherited breast and ovarian cancer. We reviewed the mutation spectrum in BRCA2-associated FA, and the spectrum and frequency of BRCA2 mutations in distinct populations. The rarity of FA due to biallelic BRCA2 mutations supports a fundamental role of BRCA2 for prevention of malignant transformation during development. The spectrum of malignancies seen associated with FA support the concept of a tissue selectivity of BRCA2 mutations for development of FA-associated cancers. This specificity is illustrated by the distinct FA-associated BRCA2 mutations that appear to predispose to specific brain or haematological malignancies. For some populations, the number of FA-patients with biallelic BRCA2 disruption is smaller than that expected from the carrier frequency, and this implies that some pregnancies with biallelic BRCA2 mutations do not go to term. The apparent discrepancy between expected and observed incidence of BRCA2 mutation-associated FA in high-frequency carrier populations has important implications for the genetic counselling of couples with recurrent miscarriages from high-risk populations.

INTRODUCTION
Fanconi anaemia (FA) is an autosomal recessive and X-linked inherited condition characterised by congenital abnormalities, and an extreme increase in cancer predisposition.1 FA cells show cross-linker sensitivity and cell-cycle perturbation, in particular in response to DNA damage. FA can be caused by mutations in at least 15 genes encoding for proteins that interact in a DNA damage response pathway including BRCA2, the gene which is mutated in the 3–5% of FA cases (FA-D1 group).1–3 Heterozygous mutations in genes of other downstream proteins, such as FANCN/PALB2 and FANCJ/BRIP1, are associated with an increased risk of breast cancer, and mutations in RAD51C lead to an increased risk of ovarian cancer.4–10 This DNA damage repair network links an uncommon, predominantly paediatric, disorder to familial breast and ovarian cancer. FA caused by biallelic mutations in BRCA2 has been recognised to often have a severe phenotype, with more extensive congenital abnormalities and a particularly strong cancer predisposition where cancers typically develop in the first decade. This pattern is in contrast with the more ‘classic’ FA phenotype, which can be quite subtle, and does not typically present with cancer in the first decade, but leads to solid tumours, such as squamous cell carcinoma (SSC) from the second and more commonly the third decade onwards.11,12 In this review, we summarise cancer-related features of biallelic BRCA2 mutations with biological implications for BRCA2 function. As monoallelic mutations in BRCA2 cause a high risk of dominantly inherited breast and ovarian cancer (HBOC), the BRCA2 mutation spectrum and frequency has been determined in many populations.13 Based on epidemiological data of the spectrum and incidence of BRCA2 mutations in the general population and the BRCA2 mutation spectrum associated with FA, we suggest some pragmatic guidelines for counselling couples at risk of a child with FA due to biallelic BRCA2 mutations in high-frequency carrier populations.

FA-ASSOCIATED BRCA2 MUTATIONS: IMPLICATIONS FOR BRCA2 FUNCTIONS DURING DEVELOPMENT
We have identified 31 FA patients in 23 pedigrees with confirmed biallelic pathogenic BRCA2 mutations using PubMed with key words ‘Fanconi anemia’ and ‘BRCA2’.14–25 We have not included the individual who subsequently was found to have biallelic mutations in FANCB underlying the FA phenotype,26 and individuals in whom identified variants in BRCA2 subsequently were classified as likely benign. While this series is based on detailed reports of only a small number of cases, most of these individuals have an FA phenotype with multiple congenital abnormalities, which in at least six cases included a combination of features of the VACTERL spectrum (vertebra, anal, cardiac, oesophageal, renal and limb abnormalities).24–28 Details of clinical features are listed in the online supplementary table S1. The spectrum of confirmed pathogenic mutations in BRCA2 in these individuals is illustrated in figure 1. Common mutations in BRCA2 are IVS7 splice site mutations,
886delGT (c.658_659del) and the Ashkenazi Jewish (AJ) founder mutation 6174delT (c.5946delT). Additionally, the mutations 3492insT (c.3264dupT) and 9424C>T (c.9196C>T) have each been identified in two pedigrees. Only three BRCA2 mutations have been recorded as homozygous in FA patients, IVS19-1 G>A (c.8487+1G>A), a 19 a 1548del4 (c.1320_1323del) deletion in exon 10 in an Algerian child born to a consanguineous couple, and the IVS7+2T>G mutation. From the distribution of mutations across the BRCA2 sequence, it is difficult to identify a distinct FA-associated cluster. Of these 31 patients, 30 developed cancer in the first 5 years of their lives. Only one patient (HSC63), who was homozygous for the carboxy-terminal mutation IVS19-1G>A, has not been reported with cancer at an early age. The majority of malignancies associated with FA caused by biallelic BRCA2 mutations are acute myeloid leukaemia (AML) and medulloblastoma (MB) and, in contrast with other forms of FA, the spectrum of malignancies in this group is much broader and also includes other embryonic tumours, such as neuroblastoma and hepatoblastoma, as well as one of the rarely reported cases of lymphoid leukaemia associated with FA. The severity of the cancer-predisposition phenotype is reflected in the occurrence of multiple malignancies in the first decade of life in seven individuals with biallelic BRCA2 mutations. SSCs, which commonly develop in the third and fourth decades of life in other FA patients have not been reported in FA-D1 patients. The absence of reported SSC could be because FA-D1 patients do not survive long enough to develop SSCs. In this context, the distribution of the specific BRCA2 mutation spectrum in FA-D1 patients has some important implications, in particular from a developmental perspective. The most common mutations in FA-D1 are IVS7 splice site mutations and the 886delGT mutation. IVS7 mutations were detected in four pedigrees, three of them being IVS7+2T>G. These mutations are thus over-represented in FA-D1 and confer fetal viability, probably through expression of splice variants that encode for BRCA2 proteins compatible with fetal viability, but not with normal haematopoiesis after birth and leukaemia prevention as, strikingly, nearly all these patients develop AML. Conversely, none of the reported FA-D1 children with a brain tumour (which in most cases was a MB) has an IVS7 splice site mutation. The 886delGT mutation, which is predicted to result in a truncated protein, was detected in four families, two of whom also carried the 6174delT. The 886delGT mutation appears also to be compatible with fetal viability, but is associated with disruption and malignant transformation, in particular during brain development. The 6174delT mutation, despite being relatively frequent in the AJ population, has not been detected in the homozygous state and is, therefore, unlikely to confer BRCA2 function compatible with fetal viability in this state. While many common BRCA2 mutations are located in exon 11, no FA patient homozygous or compound heterozygous for biallelic exon 11 mutations has been reported to date (figure 1). Additional circumstantial evidence supporting the notion of exon 11 mutations being incompatible with fetal viability comes from a study of miscarriages in BRCA2 mutation carriers which found a frequency of recurrent (three or more) miscarriages among 9/210
In the same region during the period from 1990 to 2012, but grossly affects normal development. The distinct association of 886delGT and IVS7+2T>G are not encountered in 6174delT mutations if this combination were viable. It would mean that in AJ populations as many as 1 in 19,600 population in South Africa where c.7934delG is carried by 1 in 500 people. 29 The Meyer S, et al determined the spectrum and incidence of robust estimate of the frequency of BRCA2 mutations from a population in South Africa where c.7934delG is carried by 1 in 500 people. 29 The Meyer S, et al.29 The Schematic guidelines for the risk assessment and management with respect to Fanconi anaemia and pregnancy outcome of BRCA2 mutation carriers. AJ, Ashkenazi Jewish; FA, Fanconi anaemia; HBOC, hereditary breast and ovarian cancer; PGD, preimplantation genetic diagnosis; PND, prenatal diagnosis; there have been 28 children from 20 families diagnosed with FA (S Meyer, K Chandler and DG Evans, unpublished data). FA cases were from consanguineous Asian in 10 families, and Arabic backgrounds in one family. Only the Arabic family was not of resident origin in the region for more than 20 years. Among the 28 children only two had a severe phenotype with multiple congenital abnormalities and severe bone marrow failure and/or leukaemia or brain tumour in the first 5 years of life, which can be the characteristic phenotype for FA-D1 patients.42 One of these cases was a boy of consanguineous Asian background with a homozygous FANCF mutation (c.496C>T, Q116X) (S Meyer, unpublished data). The second case of severe phenotype FA was a Caucasian British boy who had biallelic BRCA2 mutations. We have previously reported this case with the BRCA2 mutations IVS7+2T>G (c.631+2T>G) and 3827delGT (c.3599_3600delGT) who was diagnosed with AML at the age of 2 years.23 Other FA patients in our region had mutations in FANCA, FANCG and FANCD2.43 As our centre provides tertiary services for approximately 10% of the UK population, we extrapolate that there have been approximately 250–300 cases with FA in the last 20 years in the UK. In line with the incidence in our region, and from reported frequency of FA-D1 patients, we presume that less than 5% of these carry biallelic BRCA2 mutations. In Iceland, where the BRCA2 999del5 mutation is responsible for a large proportion of familial breast cancer and is carried by 0.5% of people, FA has not been diagnosed in the last 20 years (R Dietrich, ÓG Jónsson, personal communication).

Given the incidence and spectrum of BRCA2 mutations in FA and the general population, and the relative high incidence of specific mutation in distinct populations, we speculate that biallelic BRCA2 mutations might be responsible for neonatal deaths in some children with multiple abnormalities before the diagnosis of FA is made, or are simply not compatible with embryonic survival. Another possibility is that an early childhood malignancy is the main feature of FA in cases caused by biallelic BRCA2 mutations, and the diagnosis of FA is not considered. Childhood cancer as the first manifestation of BRCA2 mutation-associated FA would, in theory, result in a higher incidence of childhood cancer in offspring of BRCA2 carriers. However, no increased incidence of childhood cancer has been reported in a retrospective analysis of BRCA2 mutation carriers.44 It would be important to collect data prospectively in order to determine the impact of BRCA2 mutations on fertility, neonatal death associated with developmental defects, and childhood malignancies.

**Table 1** Suggested guidelines for genetic counselling of BRCA2 mutation carriers

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Risk of an affected child with FA due to biallelic BRCA2 mutations</th>
<th>Suggested management</th>
</tr>
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<tbody>
<tr>
<td>AJ</td>
<td>BRCA2 6174delT+</td>
<td>Consider testing for AJ BRCA1/BRCA2 founder mutations in the partner, but limited indication for PND if partner also carries 6174delT. Consider offering full BRCA2 to the partner if their family history is suggestive of HBOC although non-founder mutations are infrequent in the AJ population. Offer screening for the AJ FANC founder mutation (Meyer, personal communication).</td>
</tr>
<tr>
<td>Non-AJ</td>
<td>BRCA2+</td>
<td>Consider testing for AJ BRCA1/BRCA2 founder mutations in the partner. Offer PGD/PND if the non-AJ partner carries a mutation.</td>
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</tbody>
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**SPECTRUM AND INCIDENCE OF BRCA2 MUTATIONS IN NON-FA POPULATIONS**

Data on the spectrum and incidence of BRCA2 mutations are available for numerous populations and distinct ethnic groups.28–31 In many populations, this corresponds to the reported birth frequency of BRCA2 mutation carriers of one in 667 that we detected in the Northwest region of England.17 Common mutations in BRCA2 encountered in the general population or in cohorts with familial breast cancer of specific populations are not reflected in the spectrum of BRCA2 mutations detected in FA patients with the exception of the 6174delT mutation, which is found with a high frequency in AJ breast cancer families.28 while the more frequent FA-associated BRCA2 mutations 886delGT and IVS7+2T>G are not encountered in high frequency in the general population.36 Specific BRCA2 founder mutations have been found in several European populations31 and other distinct ethnic groups, such as the Afrikaner population in South Africa where c.7934delG is carried by 1 in 200 individuals. In the Icelandic population, 0.5% carry the 999del5 mutation (c.771_775del5),39 and as many as 1.4% of the AJ population carry the 6174delT mutation,28 which would mean that in AJ populations as many as 1 in 19,600 births would be predicted to have FA as a result of homozygous 6174delT mutations if this combination were viable.

**INCIDENCE OF FA IN POPULATIONS WITH DEFINED BRCA2 MUTATION CARRIER FREQUENCY**

In the Northwest region of England we have a reasonably robust estimate of the frequency of BRCA2 mutations from a population-based study of breast cancer of one in 667 and have determined the spectrum and incidence of BRCA2 mutations.36 38 41 In the same region during the period from 1990 to 2012, there have been 28 children from 20 families diagnosed with FA (S Meyer, K Chandler and DG Evans, unpublished data). FA cases were from consanguineous Asian in 10 families, and Arabic backgrounds in one family. Only the Arabic family was not of resident origin in the region for more than 20 years. Among the 28 children only two had a severe phenotype with multiple congenital abnormalities and severe bone marrow failure and/or leukaemia or brain tumour in the first 5 years of life, which can be the characteristic phenotype for FA-D1 patients. One of these cases was a boy of consanguineous Asian background with a homozygous FANCF mutation (c.496C>T, Q116X) (S Meyer, unpublished data). The second case of severe phenotype FA was a Caucasian British boy who had biallelic BRCA2 mutations. We have previously reported this case with the BRCA2 mutations IVS7+2T>G (c.631+2T>G) and 3827delGT (c.3599_3600delGT) who was diagnosed with AML at the age of 2 years. Other FA patients in our region had mutations in FANCA, FANCG and FANCD2. As our centre provides tertiary services for approximately 10% of the UK population, we extrapolate that there have been approximately 250–300 cases with FA in the last 20 years in the UK. In line with the incidence in our region, and from reported frequency of FA-D1 patients, we presume that less than 5% of these carry biallelic BRCA2 mutations. In Iceland, where the BRCA2 999del5 mutation is responsible for a large proportion of familial breast cancer and is carried by 0.5% of people, FA has not been diagnosed in the last 20 years (R Dietrich, ÓG Jónsson, personal communication).

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IMPLICATIONS FOR GENETIC COUNSELLING
The observations described here are relevant for the genetic assessment of couples from populations with a high incidence of BRCA2 mutations. It is possible that a significant proportion of pregnancies with biallelic BRCA2 mutations might not go to term, and it might be pertinent to explore the BRCA2 mutation carrier status in couples with recurrent miscarriages who are from populations with high BRCA2 mutation carrier frequencies.

It has been 10 years since the first clinical cases of FA due to biallelic BRCA2 mutations were reported, and there is enough information available to develop and consider pragmatic guidelines to assist with the genetic counselling of BRCA2 families (table 1). Specifically, the absence of reported cases of FA who are homoygous for the AJ 6174delT BRCA2 founder mutation is a strong indication that this state is embryonic lethal. In other clinical scenarios, the ever-decreasing cost of mutation testing by next-generation sequencing means that it is becoming realistic to consider testing in the partner of BRCA2 carriers, even if they do not belong to a known founder population. However, this must be undertaken by experienced genetic counsellors and geneticists as there is potential to generate harm and uncertainty, for example, if a variant of unknown significance is identified.

In summary, from epidemiological data, we speculate that many pregnancies with biallelic BRCA2 mutations do not go to term. This might be relevant for the genetic assessment of couples from populations with a high frequency of BRCA2 mutations. On the basis of this we have developed some pragmatic guidelines to aid counselling in at-risk families. Additionally, the spectrum of malignancies in FA caused by BRCA2 disruption implies a pleiotropic role of BRCA2 for organogenesis, in particular, haematopoiesis and brain development.

Author affiliations
1Department of Paediatric and Adolescent Oncology, University of Manchester, Manchester, UK
2Department of Paediatric Haematology and Oncology, Royal Manchester Children’s Hospital, Manchester, UK
3Young Oncology Unit, The Christie NHS Foundation Trust, UK
4Stem Cell and Leukaemia Proteomics Laboratory, University of Manchester, Manchester, UK
5Manchester Academic Health Sciences Centre, Manchester, UK
6Department of Medical Genetics, University of Cambridge, Addenbrooke’s Hospital, Cambridge, UK
7Manchester Centre for Genomic Medicine, Central Manchester University Hospitals NHS Foundation Trust, Manchester Academic Health Sciences Centre, Manchester, UK
8Manchester Centre for Genomic Medicine, Institute of Human Development, Faculty of Medical and Human Sciences, University of Manchester, Manchester Academic Health Science Centre, Manchester, UK
9Department of Obstetrics and Gynaecology, Sheffield Teaching Hospitals NHS Foundation Trust, Sheffield, UK
10Fancconi Hope Charity, Southsea, UK
11Cancer Research UK Paediatric and Familial Cancer Research Group, University of Manchester, Manchester, UK

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