Expanding the phenotypic and genetic spectrum of radioulnar synostosis associated hematological disease

Congenital radioulnar synostosis (RUS) is a rare developmental abnormality involving fusion of the bones of the forearms (radius and ulna) preventing normal supination of the affected forearm and has been recognized in orthopaedic literature since the mid-1800s. It is apparent that there is a subgroup of patients with RUS who also present with hematological abnormalities ranging from thrombocytopenia to myelodysplastic syndrome (MDS). Here, we report on a series of seven families with RUS and diverse hematological defects ranging from single cytopenias to global bone marrow failure (BMF); some individuals had severe BMF in childhood whilst others only a modest single cytopenia well into adulthood. We identify three different germline variants (two novel) in the MDS1 and EVI1 complex locus (MECOM) in five of the families. The other two families remain uncharacterized. We have further expanded the range of genotypes and phenotypes associated with RUS and hematological disease.

RUS can occur with other abnormalities in the skeleton, heart, urinary tract, as well as aneuploid syndromes.[1] RUS also occurs as part of the inherited BMF spectrum of diseases and is known as radioulnar synostosis with amegakaryocytic thrombocytopenia (RUSAT). It is usually characterized by thrombocytopenia which progresses to pancytopenia coupled with a congenital fusion of the radius and ulna. Heterozygous germline variants in two genes have been associated with RUSAT: *HOXA11* (Homeobox A11)[2] (RUSAT1, MIM#605432) and *MECOM* (MDS1 and EVI1 complex locus)[3] (RUSAT2, MIM#616738). HOXA11 is involved in upper limb development in early embryogenesis as well as normal hematopoiesis and leukemogensis. MECOM is essential

Table 1. Characteristics of cases in this study.

Family	1	2	3	4	5[§]	5[§]	5	6	7
Patient	Index case	Index case	Index case	Index case	IV-1 (Index case)	IV-3	V-1	Index case	Index case
Age at diagnosis	Childhood	NA	16 months	6 months	11 years	13 years	7 years	Birth	3 years
Nationality	NA	British	Kosovan	Argentinian	British	British	British	Portuguese	British
Variant	c.2248C>T p.Arg750Trp	c.2248C>T p.Arg750Trp	c.2248C>T p.Arg750Trp	c.2278G>C p.Pro760Ala	c.2272G>A p.Glu758Lys	c.2272G>A p.Glu758Lys	c.2272G>A p.Glu758Lys	None (*MECOM HOXA11*)	None (*MECOM HOXA11*)
PROVEAN score[†]	-4.299 deleterious	-4.299 deleterious	-4.299 deleterious	-6.948 deleterious	-3.457 deleterious	-3.457 deleterious	-3.457 deleterious		
RUS	Blt	Blt	Blt	Blt	Blt	Blt	Blt	Blt, Short radii,	Blt
Family history	Yes	No	No	No	Yes	Yes	Yes	No	No
Peripheral blood	Hemolytic anemia and MDS*	AA	Pancytopenia	Severe Pancytopenia	Normal	Thrombo-cytopenia	Normal	Pancytopenia	AA
Bone marrow	Hypercellular, erythroid dysplasia		↓ cellularity and mega-karyocytes	Hypocellular				Hypocellular	Hypocellular
Transfusion dependent	Yes		Yes		No	No		Yes	
HSC transplant	Under Consideration	Yes		Yes	No	No	No		Under Consideration
Chromosome breakage test	Normal		Normal	Normal	Normal	Normal		Normal	Normal
Hand abnormality	Blt, short 5th finger, nail ridging	Nail dysplasia			Mild nail abnormality				
Facial abnormality			Abnormal facies, ear abnormalities	Small head					
Other	Splenectomy		Tetralogy of Fallot	Clubfoot	Late onset hearing loss	Moya Moya disease		Reticular hyperpigmentation, Premature	Premature, short stature, Immunodeficiency

NA: not available; Blt: bilateral; MDS: myelodysplastic syndrome; *this patient had aplastic anemia in childhood which resolved, then at age 37 years he presented with trilineage MDS (subtype: refractory cytopenia); AA: aplastic anemia; †PROVEAN (Protein Variation Effect Analyzer) is a software tool which predicts whether an amino acid substitution or indel has an impact on the biological function of a protein. A score of -2.5 or less is predicted to be deleterious.

for the proliferation of hematopoietic stem cells and is expressed in developing limbs.[4]

We identified a cohort of nine cases from seven families with RUS and variable hematological disease. The clinical characteristics of these patients (including one we have previously described[5]) are detailed in Table 1. Radiographs of the radius and ulna fusions from families 4-6 (Figure 1), show all cases have a very similar radiological appearance. Using Sanger sequencing, we screened the coding exons of *HOXA11* and *MECOM* in the index cases of these families. No coding variants were identified in *HOXA11*. However, we did identify coding variants in *MECOM* (NM_001105078) in seven individuals from five families. Families 1-3 shared the same variant (c.2248C>T; p.Arg750Trp: Figure 2A) as reported by Niihori *et al.*[3] Novel variants were identified in families 4 and 5. These were c.2278G>C; p.Pro760Ala and c.2272G>A; p.Glu758Lys, respectively (Figure 2B). Based on genetic studies and clinical presentation, an autosomal dominant inheritance pattern was observed in families 1 and 5. From the information available it appears that the variants in families 2-4 were *de novo* which is in agreement with the initial report.[3] After direct Sanger sequencing, families 6 and 7 (Figure 2C) remain uncharacterized despite having a similar presentation, suggesting further genes may be involved in this disorder. There are three reports in literature[5-7] of patients presenting with pancytopenia and RUS with no indication of the underlying genetic cause being given, as well as a more unusual case of RUS-associated B-cell acute lymphoblastic leukemia[8] where the BCR-ABL gene fusion is unlikely to explain the RUS (*Online Supplementary Table S1*). It is unlikely that a large germline *MECOM* deletion has been missed in families 6 and 7 as reports describe two cases where deletions encompassing some or all of *MECOM* result in thrombocytopenia but not the associated RUS.[9,10] Further studies are needed in these two families to determine the underlying basis of the disease.

Reviewing literature, the first disease gene to be associated with both RUS and bone marrow failure was *HOXA11*. The heterozygous variant c.872delA, p.Asn291ThrfsX3 was identified in six individuals from two families (*Online Supplementary Table S1*)[2] and causes a premature truncation of *HOXA11*. In both families the variant was inherited from the father. Interestingly, both fathers showed skeletal abnormalities of the arm but neither had any hematological disease. All the affected children presented with thrombocytopenia from birth, with three out of the four undergoing BMT. Recently, several papers have been published identifying germline variants in *MECOM* in patients with various bone marrow failures either with or without the presence of RUS (*Online Supplementary Tables S1 and S2*).[2,3,11-13] From these reports, together with findings of this study, we are able to demonstrate that even with the same variant the age of onset and the severity of BMF is highly variable. We observe that the *MECOM* variant p.Arg750Trp is a recurrent change that can present with a variety of hematological defects in association with RUS. In five out of the six families with this variant (families 2 and 3 in this study, and cases described in references 3, 10, 12) the disease appears *de novo*, with presentation very early in

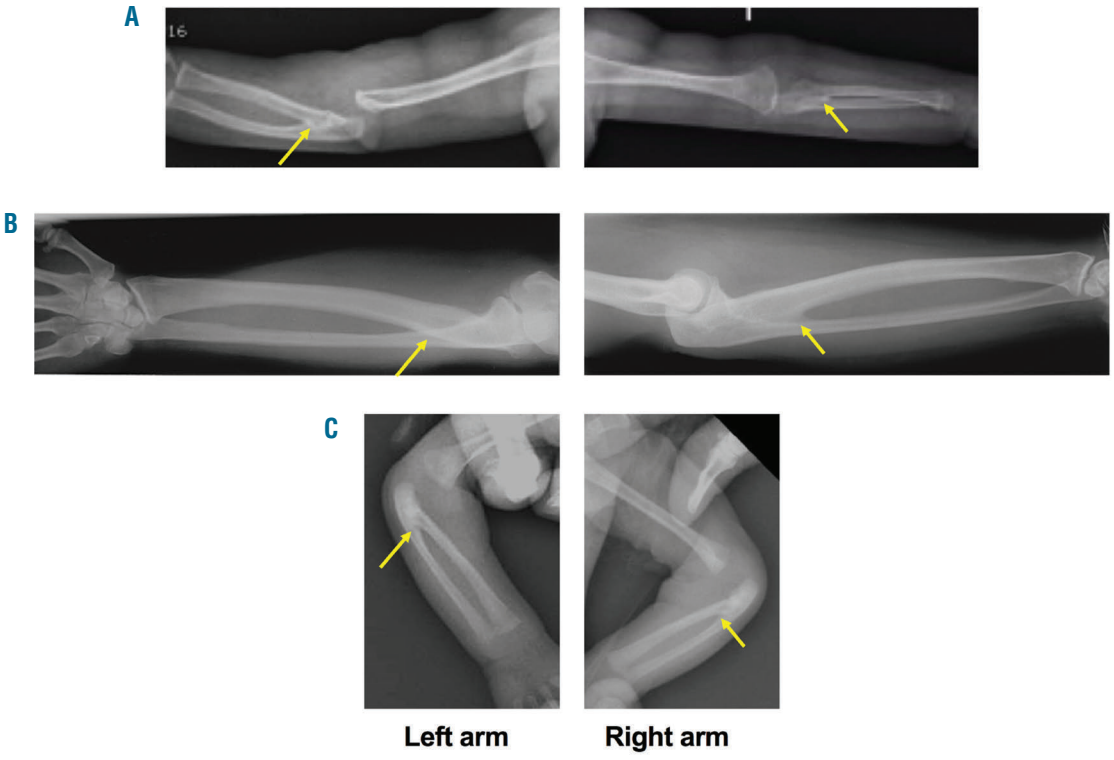

Figure 1. X-rays of the forearms showing proximal fusion of the radius and ulna. (A) Radiographs of both arms from the index case of family 4. (B) Affected mother of family 5 (generation III). (C) Index case of family 6 in which neither *HOXA11* nor *MECOM* variants were detected. Arrows highlight proximal fusion of the radius and ulna.

infancy/childhood, and all cases required a BMT. The sixth case with p.Arg750Trp (index case family 1) shows dominant inheritance pattern and the hematological involvement progressed from aplastic anemia to myelodysplastic syndrome (MDS); this presentation of RUS and development of MDS in adulthood is similar to the family reported by Ripperger *et al.*[12] even though the causative variant is different. Autosomal dominant inheritance was also seen in a second family in our cohort (family 5). The hematological abnormality in the affected cases from family 5 was variable: ranging from normal blood count, mild single cytopenia to severe pancytopenia, again demonstrating variability in severity and age of onset. Interestingly, there are reports of seven patients with germline heterozygous variants (including two deletions) affecting *MECOM* where there is no presence of RUS but the severe associated hematological disease required treatment with BMT.[9-11] These patients form a distinct group as they were sporadic, *de novo* cases who presented with disease in infancy. The reason behind this difference in phenotype is unclear at present.

All the heterozygous *MECOM* variants reported in this study are highly conserved from humans to yeast (Figure 2D), cluster within 10 amino acids (aa750-760) and impact on either the highly conserved Cys2His2 zinc finger motif (zinc finger 8, aa733-755) or the adjacent linker motif (aa756-760). Preliminary data suggest levels of MECOM appear to be reduced in lymphoblastoid cell lines heterozygous for p.Glu758Lys (*Online Supplementary Figure S1*). Cys2His2 zinc fingers are one of the most common DNA-binding motifs found in eukaryotic transcription factors and usually occur in groups allowing for multiple tandem contacts along the DNA. *EVI1* has 2 zinc finger domains; proximal domain contains 7 motifs and the distal contains 3 motifs (Figure 2E) and it has been shown that these 2 domains can have different functions.[14] Studies removing the whole of the 8th zinc finger domain have shown that this can block granulopoiesis confirming this region is involved in hematopoiesis. All germline variants identified to date in *MECOM* are shown in Figure 2E. It is noteworthy that all variants associated with the co-presentation of RUS and hematological disease cluster in region spanning zinc fingers 8 and 9. The variants observed in patients with hematological disease without RUS (verified by x-ray)[11] are more widely distributed throughout the complex, including two deletions that either remove the MDS1 part of the complex or the entire gene region.[9,10] Further reports may help to clarify whether there is a definitive genotype-phenotype correlation for disease associated variants in *MECOM*.

In this study, we have genetically characterized patients from five out of seven families with RUS and hematological disease. As well as identifying novel pathogenic *MECOM* variants, we show that three of the families share the same previously identified *MECOM* variant. The differences in presentation have enabled us to expand the clinical phenotype from a severe global bone marrow failure requiring transplantation that presents very early in infancy to a syndrome that presents with

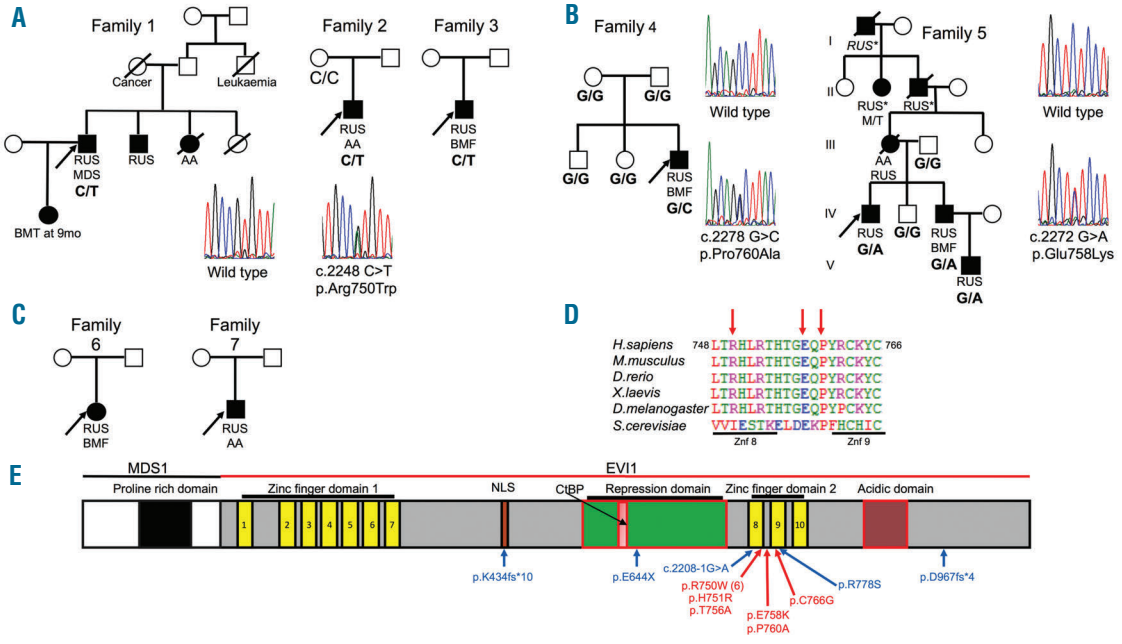

Figure 2. Family trees of all cases and *MECOM* variants identified in this study. (A) Families 1-3 share the same heterozygous variant in *MECOM*. (B) Family trees and sequencing traces for families 4 and 5. (C) Families 6 and 7 do not have variants in either *MECOM* or *HOXA11*. Unless indicated by a genotype, a DNA sample was unavailable for sequencing. Representative sequence traces of both the wild type and the variant are shown. *RUS*: radioulnar synostosis; AA: aplastic anemia; MDS: myelodysplasia; BMF: bone marrow failure; M/T: macrocytosis and thrombocytopenia; RUS*: radioulnar synostosis is presumed from the clinical description; NAD: no abnormality detected; arrow indicates the index case. (D) Protein sequence from different species showing the conservation of the variants identified in this study (red arrows). The underlined residues highlight part of zinc fingers 8 and 9. H.sapiens (human) NP_001098548.2, *M.musculus* (mouse) XP_011247963.1, *D.rerio* (zebra fish) XP_017206701.1, *X.laevis* (African clawed frog) NP_001089139.1, *D.melanogaster* (fruit fly) NP_001260545.1, *S.cervisiae* (yeast) KZV08884.1. E - Schematic representation of *MECOM* encompassing both the MDS1 and the EVI1 components of the complex. All germline variants identified to date are mapped on to this diagram. Red arrows/text - variants identified in patients with RUS and hematological defects. Blue arrows/text – variants in patients with hematological defects but no RUS. (6) – total number of different families reported for this variant. Protein numbering is relative to the EVI1 component of the complex only (NP_001098548.2). NLS: nuclear localisation signal; CtBP: C-terminal binding protein domain.

variable hematological disease in adults. The disease can also be inherited in families in a dominant manner and in these cases the hematological involvement is more variable both in terms of severity and age of presentation. It is also notable that the hematological features can be very variable, even amongst affected members of the same family as exemplified by families 1 and 5. Lack of variants in *MECOM* and *HOXA11* in two of the families, together with uncharacterized families in the literature, suggest there may be other disease genes to be identified. Also, in light of the number of BMF cases where *MECOM* variants can occur independently of the development of RUS, a genetic screen of *MECOM* should be undertaken in all new patients with BMF, particularly if there is no family history of disease. Finally, it has become clear that RUS-associated hematological abnormalities are frequently more global and variable, rather than being limited to thrombocytopenia. The description RUS-associated hematological disease (RUSHD) is therefore perhaps more appropriate than RUS-associated amegakaryocytic thrombocytopenia (RUSAT) which was initially coined for the disease features observed in patients with germline *HOXA11* or *MECOM* variants.

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