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REPORT

A novel RFC1 repeat motif (ACAGG) in two Asia-Pacific CANVAS families

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Cerebellar ataxia, neuropathy and vestibular areflexia syndrome (CANVAS) is a progressive late-onset, neurological disease. Recently, a pentanucleotide expansion in intron 2 of *RFC1* was identified as the genetic cause of CANVAS. We screened an Asian-Pacific cohort for CANVAS and identified a novel *RFC1* repeat expansion motif, $(ACAGG)_{exp}$, in three affected individuals. This motif was associated with additional clinical features including fasciculations and elevated serum creatine kinase. These features have not previously been described in individuals with genetically-confirmed CANVAS. Haplotype analysis showed our patients shared the same core haplotype as previously published, supporting the possibility of a single origin of the *RFC1* disease allele. We analysed data from >26 000 genetically diverse individuals in gnomAD to show enrichment of (ACAGG) in non-European populations.

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Introduction

Cerebellar ataxia, neuropathy and vestibular areflexia syndrome (CANVAS) (OMIM: 614575) is a recessive late-onset neurological disease with slow progression (Migliaccio *et al.*, 2004; Szmulewicz *et al.*, 2011*a*, *b*). CANVAS was first characterized as a distinct syndrome by Szmulewicz *et al.* in 2011, who determined that non-length dependent sensory deficit is secondary to neuronopathy and is an integral part of the syndrome (Szmulewicz *et al.*, 2011*a*). Prominent clinical features associated with CANVAS include imbalance, saccadic smooth pursuit, downbeat nystagmus and autonomic dysfunction (Wu *et al.*, 2014), gait ataxia, dysarthria, sensory symptoms (Cortese *et al.*, 2020) and an impaired visually enhanced vestibulo-ocular reflex (Migliaccio *et al.*, 2004; Szmulewicz *et al.*, 2011*a*). Chronic cough has been reported to arise years before neurological symptoms (Wu *et al.*, 2014). Pathologically, patients typically display cerebellar atrophy particularly affecting the vermis and hemisphere crus I, and marked atrophy of dorsal root ganglia. Nerve conduction studies show absent sensory nerve action potentials, often in conjunction with normal motor conduction (Szmulewicz *et al.*, 2011*a*, *b*; Umeh *et al.*, 2016). Nerve ultrasound shows characteristically small peripheral nerves (Pelosi *et al.*, 2018).

A biallelic pentanucleotide expansion in the second intron of the replication factor C subunit 1 (*RFC1*) gene was recently identified as a genetic basis for CANVAS (Cortese *et al.*, 2019). This locus displays considerable heterogeneity. The pathogenic *RFC1* expansion $(AAGGG)_{exp}$ differs from the reference allele $(AAAAG)_{11}$ in both motif sequence and the number of repeats (Cortese *et al.*, 2019; Rafehi *et al.*, 2019). The initial report also described two other non-pathogenic expansions observed within healthy individuals: $(AAAAG)_{exp}$ and $(AAAGG)_{exp}$ (Cortese *et al.*, 2019). Two additional motifs were subsequently described: $(AAGAG)_{exp}$ and $(AGAGG)_{exp}$ (Akçimen *et al.*, 2019). However, no homozygous individuals were observed for either configuration, so pathogenicity of these motifs remains uncertain. Further adding to the complexity of the locus is an alternate pathogenic allele configuration $(AAAGG)_{10\text{-}25}(AAGGG)_{exp}(AAAGG)_{exp}$, which appears to be specific to the Māori population (Beecroft *et al.*, 2020).

By screening an Asian Pacific cohort for CANVAS, we discovered three patients with a novel, likely pathogenic *RFC1* repeat motif $(ACAGG)_{exp}$. These patients show additional clinical features that have not been previously described in genetically defined CANVAS, including fasciculations and elevated creatine kinase levels. We also show these patients share the same core haplotype as previously described, which further supports a single origin of the CANVAS disease allele.

Materials and methods

Cohort

This project was approved by the Human Research Ethics Committee of the University of Western Australia (RA/4/20/1008) with reciprocal ethics approval from Curtin University (HRE2019-0566). DNA samples from whole blood were obtained from the Diagnostic Genomics Department (PathWest) for each of the probands and additional family members, where available. Clinical data were collected by the corresponding clinicians.

The patients described here represent a subset of a larger CANVAS cohort that was genetically screened for the *RFC1* pathogenic repeat expansion. Twenty-nine of these patients have been described elsewhere (Beecroft *et al.*, 2020; Cortese *et al.*, 2020).

Family Indo1

This family consisted of two affected brothers and five unaffected siblings (Fig. 1A). The parents were second cousins. The family resides in Indonesia, but are of Chinese descent. Further information about their ancestry was not available.

Patient N1

This female patient is an isolated proband from Niue for whom no familial DNA was available. Although there was no recorded consanguinity, the population of Niue is ~1500 individuals (Australian Department of Foreign Affairs and Trade, 2019). Her mother was of Niuean descent, and her father had one Niuean and one English parent.

Preliminary genetic screening

A combination of flanking PCR and repeat primed-PCR (RP-PCR) was used to genotype each individual, described by Cortese *et al.* (2019). In brief, flanking PCR is performed with primers that bind just outside the *RFC1* repeat region. Absence of a PCR product suggests the presence of a biallelic expansion that is too large to be amplified with the standard PCR extension time. Individuals that did not show a product by flanking PCR were subsequently tested by RP-PCR for the three previously known *RFC1* repeat expansion motifs: (AAAAG), (AAAGG), and (AAGGG). Reaction composition, thermocycling conditions and primers are provided in Supplementary Table 1.

PCR-based sequencing of the *RFC1* expansion sequence

A multi-step PCR protocol was developed for amplification and subsequent Sanger sequencing of the novel *RFC1* repeat motif. Long-range PCR was used to amplify the repeat locus, followed by nested PCR to provide clearer sequencing downstream. PCR products of the expected size (~355 bp) were purified by gel extraction or band stab PCR (Wilton *et al.*, 1997) to enrich for desired target amplicons. Reaction composition, thermocycling

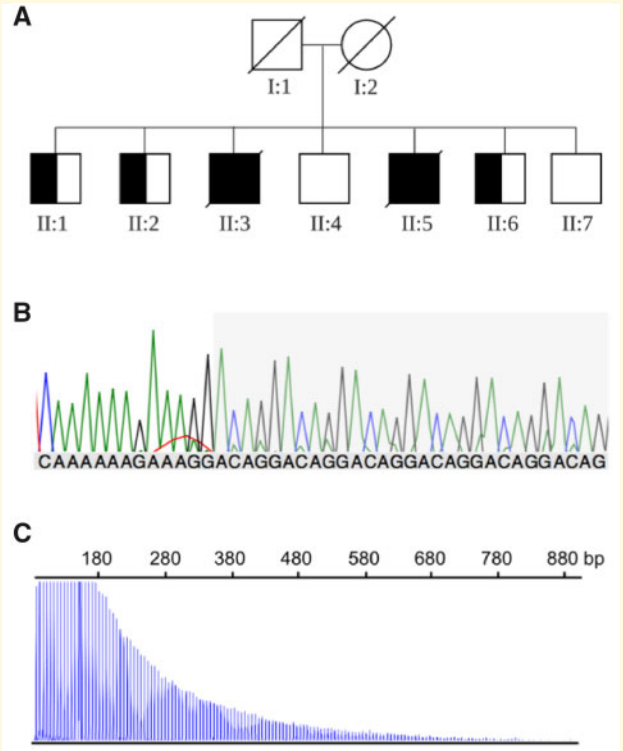

Figure 1 Novel configuration of the *RFC1* expansion in an Asian Pacific family. (**A**) Pedigree of Family Indo1. Half-shaded symbols represent individuals identified as (ACAGG) repeat expansion carriers by flanking PCR and RP-PCR. (**B**) Representative Sanger chromatogram of long-range, nested PCR products containing the novel (ACAGG) expansion at the *RFC1* locus. The grey shaded region indicates the (ACAGG) repeat sequence. (**C**) Representative positive RP-PCR fragment analysis result for the (ACAGG) repeat expansion.

conditions and primers are provided in Supplementary Table 1. Purified products were Sanger sequenced at the Australian Genome Research Facility (AGRF).

ACAGG repeat primed PCR

Following the discovery of the novel (ACAGG) motif by Sanger sequencing, we designed an ACAGG-specific RP-PCR. This allowed confirmation of the motif sequence and visualization of any large interruptions or alternate motifs present in the expansion. Primer sequences, and reaction and thermocycling conditions are provided in Supplementary Table 1. Fragment length separation was performed by AGRF.

Southern blot

Southern blot was performed as described in Cortese *et al.* (2019).

Next-generation sequencing

Illumina whole exome sequencing (WES) was performed on both affected brothers from Family Indo1 (Patients II:3 and II:5). Whole genome sequencing (WGS) was performed on Patient N1. Paired-end sequencing reads (150 bp) were generated using Novaseq 6000 sequencing (Illumina) with a 30-fold average read depth. The BAM file was viewed with Integrative Genomics Viewer software (IGV) (version 2.7.0, Broad Institute) with soft-clipping to facilitate visualization of reads that contained part of the repeat configuration. All sequencing was performed by AGRF following GATK4 best-practices (Poplin *et al.*, 2017).

Haplotype analysis

For Patient N1, we compared the WGS against the selected markers used for the haplotype analysis by Cortese *et al.* (2019) (spanning chr4: 38157510-40712481, hg19). For Individuals Indo1 II:3 and II:5, informative HapMap2 markers were extracted from exome sequencing data using Linkdatagen (Bahlo and Bromhead, 2009), and prepared for analysis with Merlin (Abecasis *et al.*, 2002). Markers were excluded if they were covered to a read depth of $<$20-fold. Merlin was used to generate the most likely haplotypes for these individuals.

Frequency of the (ACAGG) motif in the gnomAD dataset

Analysis of 26 745 ethnically diverse samples from gnomAD v3 (Karczewski *et al.*, 2020) was performed with ExpansionHunter Denovo software (Dolzhenko *et al.*, 2020). Carrier frequency estimates were performed for populations with $>$1000 individuals (Richards *et al.*, 2015) that had not been through a significant genetic bottleneck.

Data availability

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Results

Cohort and clinical features

Family Indo1

Individuals II:3 and II:5 presented with weakness about the ankles, poor balance and chronic cough at 55 and 54 years of age, respectively. Muscle wasting was initially restricted to the calf muscles but progressed to the anterior muscles below the knee and the intrinsic muscles of the hand and forearm. Fasciculations also became visible. Creatine kinase levels were elevated, ranging between 580 and 1020 U/l (normal $<$ 195). Deep tendon reflexes were initially globally reduced but deteriorated over time until they were absent. Cerebellar signs included saccadic interruption of eye movements and a wide-based gait, and later in life, dysarthria. Both individuals had an abnormal vestibulo-ocular reflex. Nerve conduction studies showed severe sensorimotor peripheral neuropathy. Muscle biopsy showed atrophic myofibres and group atrophy, consistent with a neurogenic cause. Electron microscopy of the muscle showed subsarcolemmal accumulation of pleomorphic mitochondria with large electron-dense inclusions. MRI of the head showed progressive

atrophy of the cerebellum, principally of the vermis, and thinning of the brainstem. The family returned to Indonesia and were lost to follow-up; the affected individuals are now deceased.

Patient N1

The patient first presented aged 57 when a CT scan performed for syncope found evidence of cerebellar atrophy. Prior to this, the patient had experienced severe leg cramps and poor balance for ~10 years. She had difficulties with speaking quickly and experienced frequent choking. Examination showed gaze-evoked nystagmus with some downbeat component, broken smooth pursuit, and positive head impulse test. Limb examination showed widespread fasciculations, absent reflexes, loss of vibration sense to the costal margin, loss of position sense distally with pseudoathetosis, and mild intention tremor. The patient could not stand with feet together or perform a tandem gait. Creatine kinase level was elevated at 502 U/l (normal <195). MRI scan showed vermal, crus1, and crus2 atrophy. Nerve conduction studies showed absent sensory potentials but normal motor studies. Electromyography showed widespread, mild, chronic motor unit loss consistent with the patient's fasciculations and elevated creatine kinase. Autonomic testing confirmed impairment of parasympathetic function. The patient experienced a slow inexorable progression of neurological symptoms until death at 71 years of age. Further information is available in Supplementary Table 2.

Genetic investigations identified a novel *RFC1* repeat configuration

The three affected individuals showed no product by flanking PCR, suggesting a biallelic expansion at the *RFC1* locus. All unaffected siblings in Family Indo1 generated a robust PCR product, suggesting at least one allele was small enough to be amplified by PCR (data not shown). These individuals were negative for the (AAAAG), (AAAGG), and (AAGGG) motifs by Sanger sequencing and RP-PCR. Our multistep amplification and sequencing protocol allowed clean Sanger sequencing of the *RFC1* repeat locus, which showed an apparently homozygous $(ACAGG)_{exp}$ repeat motif in all three affected individuals (Fig. 1B and C). Three unaffected siblings (Individuals II:1, II:2 and II:6) in Family Indo1 were heterozygous for the (ACAGG) motif, while Individuals II:4 and II:7 had two normal alleles. Southern blot was performed for Patient Indo1 II:5, showing a band of ~10 000 kb (homozygous). Given that control DNA gives a band of ~5000 kb, the expansion in our patient would be ~5000 kb. This corresponds to ~1015 repeated units (Supplementary Fig. 1).

For Patient N1, the *RFC1* locus configuration was also visible with WGS data. A number of soft-clipped reads spanned the repeat expansion and the region flanking the *RFC1* repeat locus (Fig 2). No reads contained alternative repeat configurations, indicating that Patient N1 is homozygous for the ACAGG motif.

Haplotype analysis

Comparison of the Patient N1 haplotype with that of Cortese *et al.* (2019) indicated that these individuals share the same core haplotype, as well as a subset of the 'Māori' haplotype we recently described (Beecroft *et al.*, 2020) (Supplementary Table 3). Similarly, the affected individuals in Family Indo1 shared the same 'Māori' haplotype, as extracted from WES markers (Supplementary Table 4) (Beecroft *et al.*, 2020). The reference and minor allele frequencies were extracted from the whole 1000 Genomes dataset (1000 Genomes Project Consortium *et al.*, 2015) using LDlink (Machiela and Chanock, 2015).

gnomAD analysis

Analysis of 26 745 samples from gnomAD v3 (Karczewski *et al.*, 2020) identified the *RFC1* (ACAGG) motif in seven individuals. Of these, two were African, four were South Asian, and one was East Asian. The (ACAGG) motif appears to be enriched in non-European populations, since of the 26 745 individuals analysed, 9954 were non-Finnish Europeans, 7281 were African, 4919 were admixed American/Latino, 1841 were Finnish, 1510 were South Asian, 894 were East Asian, and 346 were Ashkenazi Jewish. Haplotyping was not possible. Carrier frequency ranged from 0% in Europeans to 0.03% in Africans and 0.26% in the South Asians (Supplementary Table 5).

Discussion

Extending the heterogeneity of the *RFC1* repeat locus

Previous studies identified five different configurations of the *RFC1* intron 2 repeat expansion. Here, we identified three CANVAS patients from two families that tested negative for motifs (AAAAG), (AAAGG) and (AAGGG) by flanking PCR and RP-PCR. We therefore suspected these individuals instead harboured large biallelic expansions of an unknown motif. All three individuals were shown to carry biallelic expansions of a novel repeat unit, (ACAGG), by three independent methods. The identification of expanded repeats of the same configuration in CANVAS patients from two unrelated families suggests that this configuration is likely to be pathogenic. The ACAGG allele segregates with disease in Family Indo1.

Genotype-phenotype correlation: an extended CANVAS phenotype

The affected individuals displayed the classical CANVAS triad of ataxia, neuronopathy and vestibular areflexia (Migliaccio *et al.*, 2004; Szmulewicz *et al.*, 2011*a*, *b*, 2014; Wu *et al.*, 2014). However, they also shared phenotypic features that may be specific to this genotype, notably,

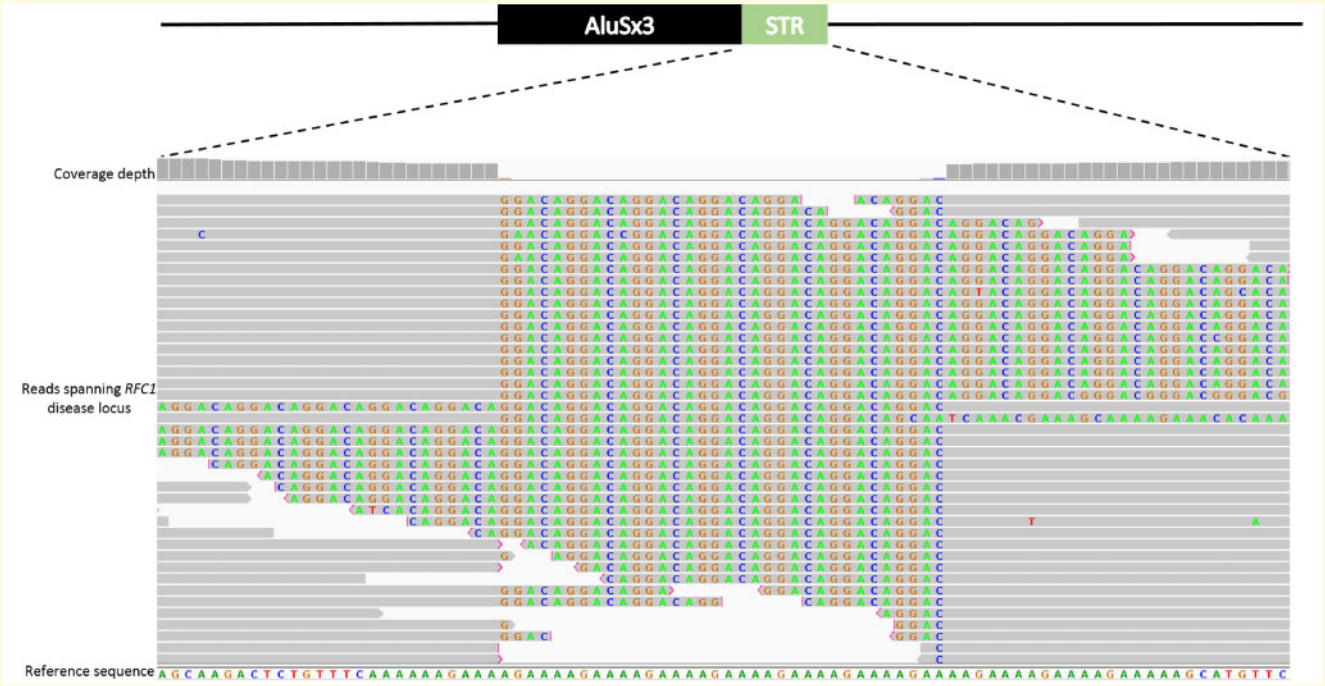

Figure 2 Visualization of the (ACAGG) repeat expansion from whole genome sequencing of Patient N1. Reads containing the *RFC1* intron 2 (ACAGG) motif are visible with soft-clipping enabled on IGV. This shows the patient is homozygous for the (ACAGG) motif.

fasciculations, elevated serum creatine kinase levels, and denervation on EMG/muscle biopsy. In contrast, subtle denervation changes were found on EMG without fasciculation or raised creatine kinase in other CANVAS patients. This suggests CANVAS may involve anterior horn cells in addition to the previously described dorsal root ganglia and cranial nerve ganglia involvement (Szmulewicz *et al.*, 2011*a*, 2014) and that this aspect of the disease may be prominent amongst patients with this genetic variant.

A single origin of a permissive haplotype?

The (ACAGG) motif shares the same core haplotype as the (AAGGG) configuration described in the Caucasian cohort from Cortese *et al.* (2019). This core haplotype is also shared by other non-Caucasian CANVAS cohorts (Beecroft *et al.*, 2020; Nakamura *et al.*, 2020). The haplotype for Patient N1 not only shared the core haplotype associated with the pathogenic $(AAGGG)_{exp}$ previously described by Cortese *et al.* (2019), but also matches a small section of the recent extended Māori haplotype (Beecroft *et al.*, 2020) (Supplementary Table 3). This suggests the 'Niue haplotype' may predate the 'Māori haplotype'. This would align with the 'out of Taiwan' theory of Austronesian migration, which postulates migration from mainland Asia through Niue and then to New Zealand (Chambers and Edinur, 2016). Together, these findings support the theory of a single origin of the disease (Rafehi *et al.*, 2019). This raises the question as to whether this common CANVAS haplotype is a permissive haplotype. It is also unclear if there is some intrinsic aspect of this haplotype that allows motif change to (AAGGG) or (ACAGG), or promotes repeat expansion into the pathogenic range. The gnomAD analysis shows that the (ACAGG) is not unique to our patients, and is enriched in non-European cohorts. CANVAS may underlie a significant proportion of undiagnosed ataxia in non-European populations.

GC content and pathogenicity

Cortese *et al.* (2019) showed that the wild-type $(AAAAG)_{exp}$ expanded to 15–200 repeats, the benign variant $(AAAGG)_{exp}$ to 40–1000 repeats, and the pathogenic motif $(AAGGG)_{exp}$ to 400–2000 repeats. These motifs contain 20%, 40% and 60% GC content, respectively. This implies a positive correlation between GC content and *RFC1* repeat expansion size. This is supported by findings from Kiktev *et al.* (2018), who showed that alteration of a yeast gene to 63% GC content raised mutation rates >6-fold compared to 43% or 31% GC content (Kiktev *et al.*, 2018). The discovery of a third, expanded *RFC1* allele with 60% GC content supports a link between GC content of the repeat, its size, and its pathogenicity.

Conclusions

We have identified a novel pathogenic *RFC1* repeat expansion motif $(ACAGG)_{exp}$ for CANVAS that appears to be

associated with the additional phenotypic features of fasciculations and elevated serum creatine kinase. Our analysis of gnomAD data shows this motif is enriched in non-Europeans, and may be a significant cause of ataxia, particularly in South and East Asian populations. All three affected individuals included in this study showed the same core haplotype that had previously been noted by Cortese *et al.* (2019). This supports the possibility of a single, ancient origin of the CANVAS allele (Rafehi *et al.*, 2019). Further work is required to determine if this is a permissive haplotype.

[Note added at proof stage: Recently, Tsuchiya *et al.* (2020) identified a single Japanese CANVAS patient with biallelic expansions at the *RFC1* locus of the (ACAGG) motif, within a cohort of 37 late onset ataxia cases. This study provides further evidence of the pathogenicity of the (ACAGG) repeat expansion and supports that it is present in East Asian populations.]

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Competing interests

The authors report no competing interests.

Supplementary material

Supplementary material is available at *Brain* online.

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