KMT2B-related dystonia (DYT-KMT2B, also known as DYT28) is an autosomal dominant neurological disorder characterized by varying combinations of generalized dystonia, psychomotor developmental delay, mild-to-moderate intellectual disability and short stature. Disease onset occurs typically before 10 years of age. We report the clinical and genetic findings of a series of subjects affected by adult-onset dystonia, hearing loss or intellectual disability carrying rare heterozygous KMT2B variants. Twelve cases from five unrelated families carrying four rare KMT2B missense variants predicted to impact protein function are described. Seven affected subjects presented with adult-onset focal or segmental dystonia, three developed isolated progressive hearing loss, and one displayed intellectual disability and short stature. Genome-wide DNA methylation profiling allowed to discriminate these adult-onset dystonia cases from controls and early-onset DYT-KMT2B patients. These findings document the relevance of KMT2B variants as a potential genetic determinant of adult-onset dystonia and prompt to further characterize KMT2B carriers investigating non-dystonic features.
Correspondence to: Alessio Di Fonzo, MD PhD
Via Francesco Sforza 35, 20122, Milan, Italy
E-mail: alessio.difonzo@policlinico.mi.it

Keywords: KMT2B; dystonia; hearing loss; DYT28; genetics

Abbreviations: DNAm = DNA methylation; MDS = multidimensional scaling; SVM = support vector machine; WES = whole-exome sequencing

Introduction

KMT2B-related dystonia (DYT-KMT2B, also known as dystonia 28, DYT28) is an autosomal dominant infantile-onset neurologic disorder. Disease onset typically occurs before age 10; however, later onset has been seldom reported. DYT-KMT2B generally presents with a progressive course evolving from lower limb into generalized dystonia with prominent cranial, cervical, and bulbar involvement. Dystonia severity is variable and ranges from minor gait disturbances to wheelchair dependence. Psychomotor developmental delay, mild-to-moderate intellectual disability, and relative short stature can precede dystonia onset or be present in isolation as the only phenotypic signature in mutation carriers. Sensorineural hearing loss has also been rarely reported. Most of the DYT-KMT2B patients described to date harbour a de novo KMT2B variant, that can show incomplete penetrance within the same family.

In this clinical and genetic report, we present twelve cases from five unrelated families (Fig. 1) carrying four rare functionally relevant KMT2B variants who presented with adult-onset dystonia or non-dystonic phenotypes including progressive hearing loss, intellectual disability and short stature.

Materials and methods

Genetic analysis

Genomic DNA was extracted from peripheral venous blood by standard salting-out procedures. Probands’ DNA was analysed by WES using the Nextera Rapid Capture Exome Library kit (Illumina, San Diego, CA, USA) and the Illumina NextSeq500 platform (Illumina), according to the manufacturer instructions. Reads were aligned against the human reference genome (hg38) using BWA and variant calling was performed with GATK4. A virtual gene panel targeted for genetic dystonias (Supplementary material) was used to filter WES data. The candidate KMT2B variants were validated by Sanger sequencing and tested in available relatives.

DNA methylation analysis

Genome-wide DNA methylation (DNAm) analysis was performed on peripheral blood DNA using Infinium Methylation EPIC BeadChip array (Illumina), according to the manufacturer’s protocol. Data pre-processing and normalization starting from IDAT files were performed as previously described. The DNAm profiles of eight affected cases (A.II.4, A.III.10, A.II.8, B.I.2, B.II.3, C.II.1, D.II.2, E.II.2) were compared with those from an in-house database including >300 samples from healthy individuals and patients with different rare neurodevelopmental disorders, using the established DNAm signature for early-onset DYT-KMT2B by means of multidimensional scaling (MDS), considering the pair-wise Euclidean distances between samples. The training of the SVM classifier was performed with a linear kernel using the e1071 R package (V.1.7) using nu-classification option. To determine the best hyperparameter and to measure the accuracy of the model, the whole data set was split in a training
Figure 1 Family pedigrees and KMT2B variants segregation. Families of the probands A.II.4, B.II.3, C.II.1, D.II.2 and E.II.1. Black, dark grey and light grey fillings indicate affected status by dystonia, hearing loss and short stature/intellectual disability, respectively. Asterisks indicate the subjects that underwent DNAm array analysis.
set (75% of samples) and a test set (25% of samples), and a 5-fold cross-validation was performed during the training process. Scores from SVM classifier below 0.25 were considered as control samples, from 0.25 to 0.5 were considered inconclusive findings, whereas >0.5 indicated predicted pathogenic variants. The selected cases were then analyzed together with 27 age- and sex-matched controls to identify the most informative differentially methylated probes. The selected subset of differentially methylated probes (Supplementary Table 2) was validated using the entire in-house data set by MDS analysis.

**Data availability**

The Ethics Committee of the IRCCS Foundation Ca’ Granda Ospedale Maggiore Policlinico (Milan, Italy) approved the study. Written informed consent for publication of clinical details, clinical images, and video recording were obtained from all involved subjects. Due to privacy and ethical concerns, supporting genetic and epigenetic data can only be made available to bona fide researchers subject to a non-disclosure agreement.

**Results**

**Clinical features**

**Family A**

Family A originated from a Sardinian village. No consanguinity was reported. All family members had normal birth and psychomotor development. At age 69, A.II.4 developed severe eyelid apraxia and pretarsal blepharospasm that led to functional blindness (Video 1). Local injections of botulinum toxin produced some benefit, but the duration of relief was less than two months. Subject A.II.5 developed at the age of 62 a dystonic head tremor and action tremor in both hands, which remained stable over the years. At age 56, Subject A.II.8 developed severe blepharospasm; two years later, he developed cervical dystonia (right torticollis and laterocollis) and neck pain (Video 1). Local injections of botulinum toxin were effective. Brain MRI was unremarkable in all three siblings. Subjects A.II.1 and A.II.7 developed isolated hearing loss in infancy. Their father (A.I.1) was reported to have developed a tremor, diagnosed as Parkinson’s disease, at the age of 50, and died at age 93. Two children of the affected Subject A.II.4 were tested (A.III.10 and A.III.11) since A.III.10 developed hearing loss in childhood, and A.III.11 displayed abnormal hand posture when writing since childhood (writer’s cramp).

**Family B**

Subject B.II.3 is a 36-year-old female born prematurely at Week 36 of gestation. Psychomotor development and school performance were normal. At the age of 19 years, she complained of a subacute motor impairment affecting the left upper limb with the development of a fixed dystonic posture within a few months. In the subsequent year, dystonia spread to the left lower limb and speech became progressively rhinolalic. The motor phenotype thereafter stabilized, whereas a progressive disturbance of ocular movements developed.

**Results**

**Clinical features**

**Family A**

Family A originated from a Sardinian village. No consanguinity was reported. All family members had normal birth and psychomotor development. At age 69, A.II.4 developed severe eyelid apraxia and pretarsal blepharospasm that led to functional blindness (Video 1). Local injections of botulinum toxin produced some benefit, but the duration of relief was less than two months. Subject A.II.5 developed at the age of 62 a dystonic head tremor and action tremor in both hands, which remained stable over the years. At age 56, Subject A.II.8 developed severe blepharospasm; two years later, he developed cervical dystonia (right torticollis and laterocollis) and neck pain (Video 1). Local injections of botulinum toxin were effective. Brain MRI was unremarkable in all three siblings. Subjects A.II.1 and A.II.7 developed isolated hearing loss in infancy. Their father (A.I.1) was reported to have developed a tremor, diagnosed as Parkinson’s disease, at the age of 50, and died at age 93. Two children of the affected Subject A.II.4 were tested (A.III.10 and A.III.11) since A.III.10 developed hearing loss in childhood, and A.III.11 displayed abnormal hand posture when writing since childhood (writer’s cramp).

**Family B**

Subject B.II.3 is a 36-year-old female born prematurely at Week 36 of gestation. Psychomotor development and school performance were normal. At the age of 19 years, she complained of a subacute motor impairment affecting the left upper limb with the development of a fixed dystonic posture within a few months. In the subsequent year, dystonia spread to the left lower limb and speech became progressively rhinolalic. The motor phenotype thereafter stabilized, whereas a progressive disturbance of ocular movements developed.

**Data availability**

The Ethics Committee of the IRCCS Foundation Ca’ Granda Ospedale Maggiore Policlinico (Milan, Italy) approved the study. Written informed consent for publication of clinical details, clinical images, and video recording were obtained from all involved subjects. Due to privacy and ethical concerns, supporting genetic and epigenetic data can only be made available to bona fide researchers subject to a non-disclosure agreement.

**Results**

**Clinical features**

**Family A**

Family A originated from a Sardinian village. No consanguinity was reported. All family members had normal birth and psychomotor development. At age 69, A.II.4 developed severe eyelid apraxia and pretarsal blepharospasm that led to functional blindness (Video 1). Local injections of botulinum toxin produced some benefit, but the duration of relief was less than two months. Subject A.II.5 developed at the age of 62 a dystonic head tremor and action tremor in both hands, which remained stable over the years. At age 56, Subject A.II.8 developed severe blepharospasm; two years later, he developed cervical dystonia (right torticollis and laterocollis) and neck pain (Video 1). Local injections of botulinum toxin were effective. Brain MRI was unremarkable in all three siblings. Subjects A.II.1 and A.II.7 developed isolated hearing loss in infancy. Their father (A.I.1) was reported to have developed a tremor, diagnosed as Parkinson’s disease, at the age of 50, and died at age 93. Two children of the affected Subject A.II.4 were tested (A.III.10 and A.III.11) since A.III.10 developed hearing loss in childhood, and A.III.11 displayed abnormal hand posture when writing since childhood (writer’s cramp).

**Family B**

Subject B.II.3 is a 36-year-old female born prematurely at Week 36 of gestation. Psychomotor development and school performance were normal. At the age of 19 years, she complained of a subacute motor impairment affecting the left upper limb with the development of a fixed dystonic posture within a few months. In the subsequent year, dystonia spread to the left lower limb and speech became progressively rhinolalic. The motor phenotype thereafter stabilized, whereas a progressive disturbance of ocular movements developed.

**Results**

**Clinical features**

**Family A**

Family A originated from a Sardinian village. No consanguinity was reported. All family members had normal birth and psychomotor development. At age 69, A.II.4 developed severe eyelid apraxia and pretarsal blepharospasm that led to functional blindness (Video 1). Local injections of botulinum toxin produced some benefit, but the duration of relief was less than two months. Subject A.II.5 developed at the age of 62 a dystonic head tremor and action tremor in both hands, which remained stable over the years. At age 56, Subject A.II.8 developed severe blepharospasm; two years later, he developed cervical dystonia (right torticollis and laterocollis) and neck pain (Video 1). Local injections of botulinum toxin were effective. Brain MRI was unremarkable in all three siblings. Subjects A.II.1 and A.II.7 developed isolated hearing loss in infancy. Their father (A.I.1) was reported to have developed a tremor, diagnosed as Parkinson’s disease, at the age of 50, and died at age 93. Two children of the affected Subject A.II.4 were tested (A.III.10 and A.III.11) since A.III.10 developed hearing loss in childhood, and A.III.11 displayed abnormal hand posture when writing since childhood (writer’s cramp).

**Family B**

Subject B.II.3 is a 36-year-old female born prematurely at Week 36 of gestation. Psychomotor development and school performance were normal. At the age of 19 years, she complained of a subacute motor impairment affecting the left upper limb with the development of a fixed dystonic posture within a few months. In the subsequent year, dystonia spread to the left lower limb and speech became progressively rhinolalic. The motor phenotype thereafter stabilized, whereas a progressive disturbance of ocular movements developed.
Table 1 Clinical and genetic features of KMT2B variants carriers

| Family | Subject | Dystonia | Age at onset (dystonia) | Dystonia onset localization | Other localizations | Dystonic tremor | Short stature | Hearing loss | Intellectual disability | KMT2B variant |
|--------|---------|----------|-------------------------|---------------------------|-------------------|----------------|--------------|-------------|-------------------------|---------------|
| A      | II.1    | -        | NA                      | NA                        | NA                | -              | -            | +          | -                       | c.3232C>T (p.R1078C) |
| A      | II.4    | +        | 69                      | Blepharospasm             | NA                | -              | -            | -          | -                       | c.3232C>T (p.R1078C) |
| A      | II.5    | +        | 62                      | Head                      | Both arms         | +              | -            | -          | -                       | c.3232C>T (p.R1078C) |
| A      | II.7    | -        | NA                      | NA                        | NA                | -              | -            | +          | -                       | c.3232C>T (p.R1078C) |
| A      | II.8    | +        | 56                      | Blepharospasm             | Neck              | -              | -            | -          | -                       | c.3232C>T (p.R1078C) |
| A      | III.10  | -        | NA                      | NA                        | NA                | -              | +            | -          | -                       | c.3232C>T (p.R1078C) |
| A      | III.11  | +        | 6                       | Hand                      | -                 | -              | -            | -          | -                       | c.3232C>T (p.R1078C) |
| B      | II.2    | -        | NA                      | NA                        | NA                | -              | +            | -          | -                       | c.7016G>A (p.R2339Q) |
| B      | II.3    | +        | 19                      | Left arm                  | Larynx, left lower limb | -              | -            | -          | -                       | c.7016G>A (p.R2339Q) |
| C      | II.1    | +        | 34                      | Both arms                 | -                 | +              | -            | -          | -                       | c.7016G>A (p.R2339Q) |
| D      | II.2    | +        | 23                      | Larynx                    | Face, both arms   | +              | -            | -          | -                       | c.2909G>A (p.R970Q)  |
| E      | II.2    | +        | 43                      | Right arm                 | -                 | -              | -            | -          | -                       | c.1918T>A (p.S640T)  |

By age 23, horizontal saccades were slow and reduced in amplitude, and in two years she developed progressive oculomotor apraxia on the horizontal gaze (Video 1). Brain MRI at age of 23 was normal. No family history of dystonia was reported; however, her mother (subject B.I.2) presented mild intellectual disability (Total IQ 58—WEIS-IV) and short stature (126 cm).

Family C
Subject C.II.1 was born at term after a difficult delivery. Since childhood, he presented writing difficulties and his handwriting was poorly understandable. At the age of 34, he developed dystonic posture and tremor of the right upper limb. Neurological examination at the age of 49 showed dystonic movements and tremor of the right upper limb. These were induced by action and modulated by position. Brain MRI showed mild enlargement of the left lateral ventricle. I-123-Ioflupane SPECT was normal. Trihexyphenidyl, levodopa and tetrabenazine were not beneficial. He achieved some improvement with botulinum toxin.

Subject D.II.2
Subject D.II.2 was born at term and had normal psychomotor development. No family history of neurological diseases was present. At the age of 23, the patient progressively developed spasmodic dysphonia with dysarthric speech, a strained and strangled voice, and voice breaks during speaking. From the age of 29, a bilateral hand dystonic tremor developed, prevalent on the right side, especially during writing; dystonia then spread to the oromandibular region and cervical region; laryngeal impairment worsened leading to a significant decrease in speech intelligibility (Video 1). Anticholinergics did not bring any benefit. Botulinum toxin injections led to moderate improvement of dystonia. Brain MRI performed at the age of 44 showed mild brain atrophy and mild symmetrical pallidal hypointensity on T2*-weighted sequences.

Subject E.II.2
Subject E.II.2 was born at term after an uneventful pregnancy. No familial history of neurological disorders was present. At the age of 43, she progressively developed upper right arm focal dystonia. Cervical spine and brain MRI were unremarkable. Several drugs (anticholinergics, benzodiazepines, baclofen, tetrabenazine, and botulinum toxin injections) were ineffective. Neurological examination at age of 59 disclosed dystonic posture of the right upper limb with abduction of the arm and flexion-pronation of the forearm that worsened on action. The remainder neurological examination was normal.

Genetic analysis
A virtual gene panel for dystonia was applied on WES data of probands A.II.4, B.II.3, C.II.1, D.II.2 and E.II.2. Four rare heterozygous KMT2B variants were identified: c.3232C>T in subject A.II.4, c.7016G>A in subjects B.II.3 and C.II.1, c.2909G>A in subject D.II.2 and c.1918T>A in subject E.II.2. No pathogenic or rare variants were found in other dystonia genes. KMT2B variants validation and segregation analyses in the families of the probands were performed by Sanger sequencing (Table 1).

The c.3232C>T (p.R1078C) is absent from population databases, but it has been already reported by Ciolfi et al. It is predicted pathogenic by all in silico prediction tools. Arginine1078 is conserved among orthologues. Previously performed functional analyses indicated that the genome-wide peripheral blood DNAm profile associated with this variant was different from that of KMT2B mutations causing childhood-onset DYT-KMT2B, suggesting a different functional impact of this missense change. The same variant was found in all the affected members of the family (A.II.5, A.II.7, A.II.8, A.III.10 and A.III.11), indicating co-segregation of the c.3232C>T with the disease (dystonia or hearing loss). The affected subject A.II.1 was an...
The clustering of the eight tested cases, as previously described.\(^8\) As a first step, we analyzed the DNA methylation patterns of eight affected individuals (A.II.4, A.III.10, A.II.8, B.II.3, B.I.2, C.II.1, D.II.2, E.II.2), six affected by adult-onset dystonia, one by hearing loss, and one by intellectual disability and short stature, carrying the four identified missense changes in the context of the epigenotype characterizing early-onset DYT-KMT2B by MDS analysis (Fig. 2A).\(^8\) The clustering of the eight tested cases, localizing far from the early-onset DYT-KMT2B group and within the controls, did not support the functional equivalence of the presently identified KMT2B missense variants with those causing early-onset DYT-KMT2B. This finding was confirmed by the low scores obtained by the SVM classifier (Supplementary Table 1). To explore the occurrence of a distinctive DNA methylation pattern shared by the patients reported here, these cases were compared with 27 age- and sex-matched unaffected subjects by linear modeling,\(^8,9\) allowing to identify 175 independent differentially methylated probes (Supplementary Table 2). This probe-set was validated considering DNA methylation data referred to 270 unaffected controls and patients with rare neurodevelopmental disorders by MDS analysis, which confirmed the occurrence of a separate cluster including all subjects with late-onset dystonia, hearing loss, and short stature-intellectual disability (Fig. 2). These specific probes did not overlap with early-onset DYT-KMT2B epigenotype, suggesting a different molecular mechanism underlying this late-onset phenotype.

Discussion

In this report, we present 12 subjects from five unrelated families carrying four rare functionally relevant KMT2B missense variants, identified by a virtual dystonia gene panel derived from WES data.

The possible pathogenic role of the identified KMT2B variants is supported by the association with a consistent disease phenotype and their very low frequency in genetic databases. Moreover, the p.R1078C and p.R2339Q co-segregated with
In conclusion, this report highlights the possible relevance of KMT2B missense variants as a genetic determinant of adult-onset dystonia and emphasizes the possibility of non-dystonic presentations of KMT2B-related disease. It is important to note that our findings represent an important first observation and need further confirmatory studies in independent pedigrees and cohorts. In this view, KMT2B gene should be considered in patients with adult-onset progressive dystonia involving the upper body part, in particular the larynx and oromandibular region and/or the upper limb. The identification of additional family members presenting with mild or even non-neurological phenotypes may represent an important clue to suggest this specific genetic aetiology.

Funding
This work was partially supported by grants from the Italian Ministry of Health (Ricerca Corrente 2022 to A.C.; Ricerca Corrente 2022 to A.D.F.; 5 × 1000, RCR-2020-23670068_001, RCR-2021-23671215 to M.T.), and Italian Ministry of Research (FOE 2019 to M.T.).

Competing interests
R.E. receives royalties from publication of Case Studies in Movement Disorders—Common and Uncommon Presentations (Cambridge University Press, 2017) and of Paroxysmal Movement Disorders (Springer, 2020). He has received consultancies as a member of the advisory board for Sanofi and honoraria for speaking from the International Parkinson’s Disease and Movement Disorders Society. M.C. has received consultancies as a member of the advisory board of PTC Therapeutics and honoraria for being invited speaker in congresses and courses organized by the International Parkinson’s Disease and Movement Disorders Society. F.M. is supported by the Michael J. Fox Foundation for Parkinson’s research. F.M. received speaking honoraria from AbbVie, Medtronic, Bial, Merz; travel grants from the International Parkinson’s disease and Movement Disorder Society; advisory board fees from Merz and Boston Scientific; consultancy fees from Merz, Boston Scientific and Bial; research support from Boston Scientific, Merz and Global Kynetic; royalties from Springer for the book ‘Disorders of Movement’; member of the editorial board of Movement Disorders, Movement Disorders Clinical Practice, European Journal of Neurology, Journal of Neurology.

Supplementary material
Supplementary material is available at Brain Communications online.
References

1. Zech M, Boesch S, Maier EM, et al. Haploinsufficiency of KMT2B, encoding the lysine-specific histone methyltransferase 2B, results in early-onset generalized dystonia. Am J Hum Genet. 2016;99(6):1377-1387.

2. Meyer E, Carss KJ, Rankin J, et al. Mutations in the histone methyltransferase gene KMT2B cause complex early-onset dystonia. Nat Genet. 2017;49(2):223-237.

3. Ma J, Wang L, Yang Y, Li S, Wan X. Identification of novel KMT2B variants in Chinese dystonia patients via whole-exome sequencing. Front Neurol. 2019;10:729.

4. Pandey S, Bhattad S, Panda AK, Mahadevan L. Late-onset KMT2B-related dystonia in an Indian patient with Normal cognition, dystonic opisthotonus and lack of oromandibular and laryngeal involvement. Parkinsonism Relat Disord. 2020;74:33-35.

5. Abela L, Kurian MA. KMT2B-Related Dystonia. GeneReviews® [Internet]. In: Adam MP, Everman DB, Mirzaa GM, et al., eds. GeneReviews is a registered trademark of the University of Washington, Seattle. University of Washington; 1993-2022. https://www.ncbi.nlm.nih.gov/books/NBK493766/.

6. Zech M, Lam DD, Winkelmann J. Update on KMT2B-related dystonia. Curr Neurol Neurosci Rep. 2019;19(11):92.

7. Ciolfi A, Aref-Eshghi E, Pizzi S, et al. Frameshift mutations at the C-terminus of HIST1H1E result in a specific DNA hypomethylation signature. Clin Epigenetics. 2020;12(1):7.

8. Ciolfi A, Foroutan A, Capuano A, et al. Childhood-onset dystonia-causing KMT2B variants result in a distinctive genomic hypermethylation profile. Clin Epigenetics. 2021;13(1):157.

9. Levy MA, McConkey H, Kerkhof J, et al. Novel diagnostic DNA methylation epissignatures expand and refine the epigenetic landscapes of Mendelian disorders. HGG Adv. 2022;3(1):100075.

10. Marogianni C, Georgouli D, Dadouli K, et al. Identification of a novel de novo KMT2B variant in a Greek dystonia patient via exome sequencing genotype-phenotype correlations of all published cases. Mol Biol Rep. 2021;48(1):371-379.

11. Careccchio M, Invernizzi F, González-Latapi P, et al. Frequency and phenotypic spectrum of KMT2B dystonia in childhood: A single-center cohort study. Mov Disord. 2019;34(10):1516-1527.