Genetics of essential tremor

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Essential tremor (ET), the cause of which remains poorly understood, is one of the most common neurological disorders. While environmental agents have been proposed to play a role, genetic factors are believed to contribute to its onset. Thus far, three gene loci (ETM1 on 3q13, ETM2 on 2p24.1 and a locus on 6p23) have been identified in patients and families with the disorder. In addition, a Ser9Gly variant in the dopamine D3 receptor gene on 3q13 has been suggested to be a risk factor. Moreover, genetically deficient animal models express a phenotype that overlaps with some clinical characteristics of the human form of the illness. Further analyses of these genetic abnormalities may lead to the identification of causative mutations and a better understanding of the molecular mechanisms in this common movement disorder.

Keywords: essential tremor; genetics; dopamine D3 receptor gene; variant; autosomal dominant; non-Mendelian inheritance

Abbreviations: ADCA = autosomal dominant cerebellar ataxia; AIS = androgen insensitivity syndrome; AR = androgen receptor gene; CAP2 = adenylate cyclase-associated protein 2 gene; CMT = Charcot–Marie–Tooth; CMTX = X-linked Charcot–Marie–Tooth; CYP2D6 = cytochrome P45011D6; C6orf79 = chromosome 6 open reading frame 79 gene; DRD3 = dopamine D3 receptor gene; DTNBPI = dystrobravin binding protein 1 gene; ERK1,2 = extracellular signal-regulated kinase 1,2; ET = essential tremor; FMRI = fragile X mental retardation 1 gene; FXTAS = fragile X-associated tremor/ataxia syndrome; Gabral = gamma-aminobutyric acid A receptor z1; GAT1 = GABA transporter subtype 1; GFOD1 = glucose–fructose oxidoreductase domain containing protein 1 gene; GMPR = guanosine monophosphate reductase gene; HMSN = hereditary motor and sensory neuropathy; HSIP3 = HSI-binding protein 3 gene; JARID2 = Jumonji AT rich interactive domain 2 gene; JNK = c-Jun NH2-terminal kinase; LD = linkage disequilibrium; LRRK2 = leucine-rich repeat kinase 2 gene; MAPK = mitogen-associated protein kinase; MCR = minimal critical region; MTHFR = methylenetetrahydrofolate reductase gene; MYLIP = myosin regulatory light chain interacting protein gene; NACP = alpha-synuclein gene; NHLRC1 = NHL repeat-containing gene 1; NOL7 = nucleolar protein 7 gene; PHACTR1 = phosphatase and actin regulator 1 gene; PMP2 = peripheral myelin protein-22 gene; RANBP9 = RAN binding protein 9 gene; SAPK = stress-activated protein kinase; SCAI, I2 = spinocerebellar ataxia gene, type 1, type I2; SIRT5 = silent mating-type information regulation-2 homologue 5 gene; SMAX1 = X-linked spinal and bulbar muscular atrophy, type 1; TBCID7 = TBC1 domain family, member 7 gene

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Clinical features and epidemiology

Essential tremor (ET), one of the most common neurological disorders, is characterized by postural tremor, which worsens with movement (Jankovic, 2002; Thanvi et al., 2006). While action tremor is the clinical hallmark of this illness, it can also be found in a variety of disorders. For the purposes of this review, we define ET according to the clinical criteria proposed in the Consensus Statement on Tremor by the Movement Disorder Society (Deuschl et al., 1998). A growing body of evidence suggests that this disorder is not monosymptomatic but heterogeneous, as it is associated in some cases with parkinsonism, myoclonus, dystonia, cerebellar dysfunction and other motor and sensory (e.g. hearing impairment) abnormalities (Jankovic, 2002; Ondo et al., 2003). Several studies have demonstrated that non-motor features (mild cognitive deficits and personality changes) may occur in patients with ET (Gasparini et al., 2001; Lombardi et al., 2001; Vermilion et al., 2001; Lacritz et al., 2002; Troster et al., 2002;
Chatterjee et al., 2004; Louis, 2005). In two recent case-control studies, patients performed more poorly on formal neuropsychological testing than control subjects without tremor. A complaint of forgetfulness and higher frequency of dementia was also marginally more common in patients with late-onset ET (Benito-Leon et al., 2006a, b). The occasional coexistence of this disorder and other neurological diseases including Parkinson’s disease, and dystonia in the same individual or the same family presents a diagnostic challenge (Geraghty et al., 1985; Jankovic, 2000; Jankovic et al., 2004; Shahed and Jankovic, 2006). Several studies have shown that a subset of ET patients may be predisposed to developing Parkinson’s disease. This association is supported by the following evidence: (1) in some Parkinson’s disease patients, a long-standing postural tremor in the hands may precede the onset of parkinsonian features by several years or decades; (2) functional neuroimaging suggests that some ET patients have dopaminergic deficit (Schwartz et al., 2004) and (3) both ET and Parkinson’s disease phenotypes have been described in some families and autopsy studies have demonstrated Lewy body pathology in brains of ET patients (Louis et al., 2006; Shahed and Jankovic, 2006).

Estimates of the crude prevalence of ET range widely from 0.008 to 22%, and factors that contribute to the broad range include differences in study design that influence validity and differences in characteristics of study populations that influence comparability of studies. Louis et al. evaluated that the prevalence of ET worldwide ranges probably from 0.41 to 3.92% by extraction data from 5 of 19 studies with the conditions that each (i) provided diagnostic criteria for ET, (ii) defined ET as an action tremor and (iii) used community-based rather than service-based designs (Louis et al., 1998; Benito-Leon et al., 2005). There are no validated diagnostic tests for ET, but several clinical criteria have been proposed, including those by the Tremor Investigation Group (TRIG), National Institutes of Health Essential Tremor Consortium and Consensus Statement on Tremor by the Movement Disorder Society (Deuschl et al., 1998; Jankovic, 2002). Lack of consensus on the diagnostic criteria for ET is an impediment to accessing accurate prevalence data.

Despite these limitations in defining the full spectrum of ET, typically it is not difficult to diagnose. Its prevalence increases in the elderly and may be as high as 14% in people over 65 years (Moghal et al., 1994). Rare cases have been reported in newborns and infants, but childhood-onset ET is not unusual (Jankovic et al., 2004), and ~5% of new ET cases arise during childhood (Louis et al., 2005). Although prevalence among adults is similar in men and women (Louis et al., 1998), the odds of developing the disorder are 3-fold higher in boys than girls. Head tremor is more prevalent in female than in male adults with ET (Jankovic et al., 2004; Louis et al., 2005). Mortality rates are not increased (Rajput et al., 1984, 2004; Jankovic et al., 1995), but the tremor may be quite troublesome and in some medically refractory cases surgical treatment (e.g. deep brain stimulation) may be necessary (Pahwa et al., 2006).

### Genetics of ET

Twin and family studies have provided evidence for a genetic basis for ET in many but not all cases (Busenbark et al., 1996; Tan et al., 2000; Jankovic and Noebels, 2005). Linkage mapping efforts have found at least three loci for familial ET (EMT1, EMT2 and a locus on 6p23) (Shatunov et al., 2006), and a susceptibility variant (Ser9Gly) in the dopamine D3 receptor gene (DRD3) has been identified by association analysis (Jeanne et al., 2006; Lucotte et al., 2006). Here we review the genetic aspects of ET, focusing on recent discoveries and how these findings may open a window into a better understanding of disease pathogenesis.

There is a wide range of familial history reported in ET patients, ranging from 17 to 100%, according to various studies (Busenbark et al., 1996), but most studies indicate that it is a familial disorder in 50–70% of patients, and the frequency of family history is inversely proportional to the age at onset (Sullivan et al., 2004; Louis and Ottman, 2006). For family studies, historical information on reportedly unaffected relatives is of limited use given the low sensitivity of family history; the neurological examination remains the only valid means of ascertaining cases of ET among relatives (Louis et al., 1999, 2001). While familial cases are less frequent in community-derived populations, they constitute a majority in those referred for medical attention (Louis et al., 2001). The occurrence of non-familial or ‘sporadic’ ET, phenomenologically identical to the familial version, is well-recognized and possible ‘genetic causes’ of sporadic ET include reduced penetrance of autosomal dominant mutations, new mutations, non-Mendelian/multifactorial inheritance and phenocopies. The genetics of ET is not well understood and twin studies provide a powerful tool to study it. Pairwise concordance in monozygotic twins was ~2 times that in dizygotic twins (0.60 monozygotic, 0.27 dizygotic), indicating that genetic and non-genetic factors contribute to pathogenesis (Tanner et al., 2001). In one community-based study the relative risk in first-degree relatives of subjects with ET was only 4.7%, much lower than the 50% expected assuming autosomal dominant inheritance with complete penetrance (Louis, 2001). This rate is also lower than would be expected for autosomal recessive inheritance (25%) and may suggest that ET is an autosomal dominant gene with very low penetrance, or not inherited as a single gene disorder but rather behaves as a complex disorder requiring interactions of environmental and genetic factors. Alternative explanations include a polygenic or mitochondrial origin (Louis, 2001), and even autosomal recessive and X-linked patterns of inheritance cannot be excluded.
(Baughman et al., 1973). Furthermore, recently Ma et al. (2006) found a non-Mendelian preferential transmission of the affected allele in several families with multiple affected members and apparent autosomal dominant inheritance. Genetic deficiency or non-genetic factors may exert sole or synthetic roles in the development of ET in independent patients or families.

Genetic loci of ET

Cytogenetic abnormality

ET-like tremor seems to be common and a clinically significant component of the male supernumerary X syndromes and supernumerary Y syndromes (Baughman et al., 1973). A 14-year-old boy with 48, XXY karyotype was reported to present with postural tremor and a slight retardation of psychomotor development. In contrast to other cases with 48, XXY syndrome, in this pubertal patient the testicles were of normal size, he had a small stature, and showed no behavioural disturbances (Donati et al., 1992). These findings suggest that dosage alteration of genes on sex chromosomes may be responsible for an ET phenotype.

Molecular studies

At least three disease loci of ET have been identified by molecular genetic analysis (Table 1).

**ETM1 (3q13, OMIM 190300)**

In 1997, Gulcher et al. (1997) mapped a familial ET gene to chromosome 3q13 (FET1; ETM1) by a genome-wide scan in 16 Icelandic families with 75 individuals affected by definite (pure) tremor using TRIG criteria (Findley and Koller, 1995), in whom FET1 was apparently inherited as a dominant trait. The ETM1 locus spans ~10 cM region around the marker D3S1267. More recently, a Ser9Gly variant in the DRD3 gene, located in the ETM1 locus, was found associated with risk and age at onset of ET (Jeanneteau et al., 2006). The DRD3 gene encodes the dopamine D3 receptor, a member of the D2 family of dopamine receptors. D3 receptors may be involved in the regulation of locomotion as DRD3 protein is expressed in the Purkinje cells of the rat cerebellum, which has been implicated in the pathogenesis of ET (Jeanneteau et al., 2006). DRD3 has been also reported to mediate ERK activation in HEK-293 cells (Beom et al., 2004). In HEK293 transfected cells, the functional Gly9 variant increased dopamine affinity 4–5 times. Furthermore, the Gly9 variant was associated with increased dopamine-mediated cyclic AMP response and the mitogen-associated protein kinase (MAPK) signal was prolonged, as compared to the Ser9 variant. In mammalian cells, at least three groups of mitogen-activated protein kinases (MAPKs) have been identified: the extracellular signal-regulated kinases (ERK1 and 2), which increase the kinase activity of ERK1/2 to regulate many cellular events such as differentiation, proliferation, cellular excitability and acute hormonal responses), the p38 protein kinases and the c-jun NH2-terminal kinases (JNKs; also referred to as stress-activated protein kinases or SAPKs) (McDonald et al., 2000). It is of interest that the leucine-rich repeat kinase 2 gene (LRRK2) G2019S and I2020T mutations, which have been associated with autosomal dominant Parkinson’s disease, have now been shown to increase the catalytic activity of the MAPKKK domain, a part of the LRRK2 protein (Deng et al., 2005b, 2006a, b), and LRRK2 mutations eventually also lead to the activation of downstream MAPK kinases. Abnormalities in the JNK signalling pathway may also account for dopaminergic cell degeneration in patients with LRRK2 mutation. An increase in MAPK activity (such as induced by the DRD3 Gly9 variant or by some LRRK2 mutations) may be a common mechanism partly responsible for the pathogenic events leading to ET and Parkinson’s disease, which may explain the observed overlap in phenotype or coexistence of ET and Parkinson’s disease in some cases (Shahed and Jankovic, 2006). It is not clear whether the Ser9Gly variant has been shown to cosegregate with the disease in the original 16 Icelandic families linked to ETM1 (Gulcher et al., 1997).

**ETM2 (2p24.1, OMIM 602134)**

In 1997, Higgins et al. (1997) mapped the ETM2 gene to a 15-cM candidate interval on chromosome 2p22–p25 by linkage analysis in a large American family of Czech descent with dominantly inherited ‘pure’ ET. The disease gene was located to a 9.1-cM interval between the D2S224 and D2S405 loci by analysing three additional, unrelated, American families with ET; the affected individuals in the four families shared the same haplotype (Higgins et al., 1998). They further found an ancestral haplotype on chromosome 2p24.1 that segregated with the ET disease phenotype in 29% American familial ET individuals (N = 45) (Higgins et al., 2003). Kim et al. (2005) reported an association analysis of three short tandem repeat (STRs) loci in 30 sporadic ET (23 classic ET and 7 non-classic ET) patients and 30 controls. Furthermore, eight specific sequence variants were observed in classic ET, but not in non-classic ET patients or healthy controls, supporting the linkage of ET to the ETM2 locus. An association between ET and an A265G substitution in the HS1-binding protein 3 gene (HS1BP3, OMIM 609359) was reported by analysis of two genes and seven transcripts within a minimal critical region (MCR) of 464 kb (Higgins et al., 2005, 2006), However, four recombination events were reported in a region <1 cM (D2S2150 to etm1234) in the large family (Higgins et al., 2005), and the MCR has been challenged (Deng et al., 2005a). Furthermore, the association with the HS1BP3 gene was neither confirmed by our extended study nor by other investigators (Deng et al., 2005a; Shatunov et al., 2005). Based on our review of previous studies (Higgins et al., 1997, 1998, 2003, 2004), we
| Chromosome position | Author | Sample size | Inheritance model | Ethnic or geography distribution | Locus-disease relationship | Candidate gene analysis |
|---------------------|--------|-------------|-------------------|----------------------------------|---------------------------|-------------------------|
| 3q13 (ETM1)         | Gulcher et al. (1997) | 16 families | AD                | Iceland                          | Related                   | Not                     |
|                     | Kovach et al. (2001) | 1 family   | AD                | Iceland                          | Not related               | Not                     |
|                     | Illarioskin et al. (2002) | 4 families | AD                | Tajik                            | Related                   | Not done                |
|                     | Lucotte et al. (2006) | 30 unrelated French ET | AD or polygenic | French                            | Related                   | DRD3-Ser9gly variant (risk) |
|                     | Jeanneteau et al. (2006) | 276 patients, 184 controls | AD or polygenic | Caucasian from America | Related | DRD3-Ser9gly variant (risk) |
|                     | Ma et al. (2006) | 4 families | AD and polygenic? | America                          | Not related               | DRD3-Ser9gly variant (exclude causative) |
| 2p24.1(ETM2)        | Higgins et al. (1997) | 1 family   | AD                | American kindred of Czech ancestry | Related                   | Not                     |
|                     | Higgins et al. (1998) | 3 families | AD                | America                          | Related                   | Not                     |
|                     | Higgins et al. (2004) | 52 ET patients, 49 controls | AD                | Singapore                        | Related                   | Not                     |
|                     | Kim et al. (2005) | 30 sporadic ET patients and 30 controls | AD                | Korea                            | Related                   | Not                     |
|                     | Higgins et al. (2005) | 21 families, 150 controls | AD                | America                          | Related | HS1BP3 (A265G variant) (causative) |
|                     | Higgins et al. (2006) | 73 familial ET, 304 controls | AD                | America                          | Not reported              | HS1BP3 (A265G variant) (causative) |
|                     | Deng et al. (2005a) | 222 familial ET, 132 controls | AD                | North America                    | Not reported              | HS1BP3 (A265G variant) (exclude causative or risk) |
|                     |                   | 1 family | AD                | North America                    | Not related               | HS1BP3 (A265G variant) (exclude causative or risk) |
|                     | Shatunov et al. (2005) | 7 families | Not reported      | America                          | Not reported              | HS1BP3 (A265G variant) (exclude causative or risk) |
|                     | Kovach et al. (2001) | 1 family | AD                | Midwestern of America            | Not related               | Not                     |
|                     | Ma et al. (2006) | 4 families | AD and polygenic? | America                          | Not related | Not                     |
| 6p23 (ETM3?)        | Shatunov et al. (2006) | 1 family | AD                | North American                   | Related                   | PHTACTR1; TBCID7; GFOD1; SIRT5; NOL7; RANBP9; LOC441130; C6orf79; JARID2; DTNBP1; MYLIP; GMPR; SCAI; CAP2; NHLRCI (no mutation) |

AD: autosomal dominant.
believe that the ETM2 locus may span \( \sim 9.1 \text{ cM} \) region, between the \( \text{D2S224} \) and \( \text{D2S405} \) loci, and the MCR should be re-evaluated.

Genetic heterogeneity in ET has been suggested by studies in several families in which the known loci have been excluded. Kovach et al. (2001) described a 38-member, 6-generation Midwestern family with ET that did not map to either the ETM1 or the ETM2 loci. In another study, four pedigrees with ET were linked to ETM1, but in one informative pedigree both ETM1 and ETM2 were excluded (Ilarioshkin et al., 2002). Ma et al. (2006) also excluded ETM1 and ETM2 loci in four pedigrees. Recently, genome-wide non-parametric and parametric linkage analysis were conducted in seven mutigenerational North American families totalling 65 patients. In two families the third ET susceptibility locus was revealed on chromosome 6p23 with maximal non-parametric linkage multipoint score 3.281 (\( P = 0.0005 \)) and 2.125 (\( P = 0.0075 \)), respectively. Linkage to ETM1 and ETM2 was not evident in any of these families. Fifteen genes were selected as plausible candidates and none of them was found to bear pathogenic mutations (Shatunov et al., 2006).

**Candidate gene analysis for ET**

Many studies have documented an overlap between the ET phenotype and other neurological diseases including Parkinson’s disease, dystonia, myoclonus, hereditary peripheral neuropathy and other neurological disorders (Jankovic, 2002; Shahed and Jankovic, 2006). Therefore, analyses of gene abnormalities known to cause the associated neurological disorders may provide insight into the genetics of ET.

**Analysis of Parkinson’s disease-associated genes**

ET has been hypothesized to be a risk factor for the development of Parkinson’s disease and some patients with Parkinson’s disease report a long-standing history of bilateral upper extremity postural tremor long before the onset of parkinsonian features, such as rest tremor, bradykinesia and rigidity. While patients with Parkinson’s disease may also have postural tremor, the Parkinson’s disease-related postural tremor often occurs after a long latency, lasting \( \sim 10-20 \text{ s} \) (up to a minute or even longer), whereas there is usually no delay in the onset of postural tremor caused by ET when the arms assume horizontal position (Jankovic et al., 1999). Mutations in the parkin gene is the most common cause for early onset Parkinson disease (EOPD), which is responsible for 49% of familial EOPD and 18% of sporadic EOPD (Lucking et al., 2000). No mutation in the parkin gene was identified in 110 unrelated Italian ET patients (Pigullo et al., 2004). Several studies observed an association of alpha-synuclein haplotypes including NACP-Rep1 (A 263 bp allele in the alpha-synuclein promoter region) with Parkinson’s disease, but other studies failed to confirm this association and an inverse association between the alleged risk allele and Parkinson’s disease was reported in a Japanese population (Kruger et al., 1999; Farrer et al., 2001; Mizuta et al., 2002; Holzmann et al., 2003; Spadafora et al., 2003; Pals et al., 2004; Hadjigeorgiou et al., 2006). Recently, NACP-Rep1 was found associated with an increased risk of Parkinson’s disease by analysis of 2692 cases and 2652 controls (Maraganore et al., 2006). Tan and colleagues (2000) confirmed that the 263 bp variant was significantly more frequent (OR = 6.42) in American ET patients (46 cases) compared with healthy controls (100 cases). Pigullo et al. (2003), however, repeated the association study on 106 Italian patients and 90 controls and failed to identify all 13 alpha-synuclein-specific haplotypes as susceptibility factors for ET. The contrasting results and lack of replication for the association of such variant with ET could depend on the very small number of patients and controls in both studies, and therefore these results are not conclusive and larger studies would be necessary to address this issue. Of interest was that one female Parkinson’s disease patient harboring LRRK2 IVS33 + 6T \( \rightarrow \) A variant presented initially with a typical ET phenotype and her symptoms responded well to propranolol (Skipper et al., 2005). Investigation of this variant in ET or Parkinson’s disease with ET patients may provide some insights into the genetics of ET. We found none of LRRK2 G2019S, I2012T and I2020T mutations in 272 ET patients, suggesting that they are rare causes of Caucasian ET (Deng et al., 2006a) and other mutations in the LRRK2 gene may be investigated in ET patients. Although an association between cytochrome P450IID6 (CYP2D6) variant and Parkinson’s disease has been reported, the study of Agundez et al. (Agundez et al., 1997) indicates that variants in the CYP2D6 gene do not seem to be a major factor in determining susceptibility to ET.

**Analysis of dystonia-associated gene**

Although the frequent coexistence of ET and dystonia has been reported in individual families (Jankovic et al., 1997), and autosomal dominant idiopathic torsion dystonia shares some phenotypic features with ET, such as postural tremor in body parts not affected by dystonia (Jankovic and Mejia, 2005), tight linkage to the DYT1 locus on chromosome 9q32-34 was excluded in two independent studies by analysis of 13 families with ET (Conway et al., 1993; Durr et al., 1993). In 2002, Ilarioshkin et al. (2002) reported that mutation analysis of the DYT1 gene did not reveal the typical GAG deletion in ET patients.

**Analysis of other genes**

Postural tremor similar to that seen in ET has been reported in patients with X-linked spinal and bulbar muscular atrophy, type 1 (SMA1, OMIM 313200), also called Kennedy disease, associated with androgen insensitivity syndrome (AIS; OMIM 300068), which is caused by a mutation characterized by expansion of CAG repeats in the androgen receptor gene (AR, OMIM 313700) on the
X chromosome (La Spada et al., 1991; Jakubiczka et al., 1997; Sperfeld et al., 2002). A man diagnosed with ET, but found to have increased CAG repeats in the AR gene consistent with Kennedy disease, has been reported (Kaneko et al., 1993). Although he had postural tremor of his fingers, the diagnosis of Kennedy syndrome is supported by the presence of fasciculations in facial muscles and long-duration, high-amplitude polyphasic motor units, with decreased recruitment on voluntary contraction in limb muscles along with evidence of motor neuropathy by electromyographic studies.

Spinocerebellar ataxia type 12 (SCA-12) is a slowly progressive autosomal dominant cerebellar ataxia (ADCA) that differs from other SCAs because it typically begins with tremor of head and arms, often diagnosed as ET. Nicoletti et al. (2002) investigated 30 patients with familial ET from southern Italy and found none with the SCA-12 mutation.

Fragile X-associated tremor/ataxia syndrome (FXTAS) is a progressive adult-onset tremor/ataxia syndrome caused by premutations in the fragile X mental retardation 1 gene (FMR1). Major features of the syndrome include intention tremor, gait ataxia and parkinsonism in men over 50 years of age (Leehey et al., 2003; Jacquotmont et al., 2004), and studies of ours and others showed permutation of FMR1 probably plays little or no role in the pathogenesis of ET in Caucasian and Asian patients (Deng et al., 2004; Garcia et al., 2004; Tan et al., 2004).

G677T variant of methylenetetrahydrofolate reductase gene (MTHFR) has been associated with neurodegenerative disorders including Parkinson’s disease and Alzheimer’s dementia (Chapman et al., 1998; Pollak et al., 2000; Yasui et al., 2000; Nakaso et al., 2003). Sazci et al. (2004) reported that the C677T/A1298A compound genotype provided protection for ET, while the MTHFR 677T, 1298C alleles and MTHFR T677 genotype and T677/A1298A, and C677C/C1298C compound genotypes are genetic risk factors for ET in Turkey. The correlations must be confirmed in different ethnic populations and by functional studies.

Potential loci and genes of ET

ET-like tremor was found in patients with hereditary neuropathy including hereditary motor and sensory neuropathy (HMSN; Charcot–Marie–Tooth, CMT) and the Roussy–Levy syndrome (RLS, OMIM 180800), etc (Cardoso et al., 1993; Auer-Gruembach et al., 1998). ET-like tremor was observed in an X-linked CMT (CMTX) patient who carried 13-bp deletion in the connexin-32 gene (Ryan et al., 2005). Although mistimed peripheral inputs due to neuropathy may cause tremor irrespective of an intact central processor (Bain et al., 1996), some features of ET can be part of the phenotypic spectrum of some peripheral neuropathies and therefore genes causative of these neuropathies including connexin-32 and the peripheral myelin protein-22 gene (PMP22) could be regarded as potential candidates for ET.

Animal models with genetic deficiency

Animal models are important because they provide insights into the pathophysiology of human disease and may be useful in the development of novel drugs. Gamma-aminobutyric acidA receptor α1 (Gabra1−/−) mice were reported to exhibit postural and kinetic, alcohol-responsive tremor that is characteristic of ET disease (Chiu et al., 2005), but no pathogenic mutations in the GABRA1 gene have been found by testing 76 patients with familial ET (Deng et al., 2006c). Mouse GABA transporter subtype 1 (GAT1) knock out mice exhibit gait abnormality, constant 25–32 Hz tremor, which is aggravated by flunitrazepam, reduced rotarod performance and reduced locomotor activity in the home cage. As disturbed GABA-ergic transmission may play a role in the pathogenesis of ET, suggested by low CSF GABA concentrations in ET patients compared to controls (Mally et al., 1996), and the tremor can be suppressed by medications that work by GABA-ergic mechanisms, including alcohol and benzodiazepines, human GAT1 gene may be a possible candidate gene for ET.

Current problems in ET genetics and prospects for strategy

Although the preponderance of data supports the view that ET susceptibility is inherited in an autosomal dominant pattern, other models should be considered. Further understanding of the extent of familial aggregation, extent of genetic heterogeneity and mode of inheritance is essential for clinical counselling and for further research aimed at localizing and identifying susceptibility genes.

The various terms used in the study of genetics of various disorders, including ET, need to be clearly defined. Thus, the term ‘sequence variation’ is used to prevent confusion with the terms ‘mutation’ and ‘polymorphism’. The term ‘mutation’ should be reserved for a sequence variation that is disease-causing or apparently disease-associated, although it can also be used to describe any sequence change. However, a polymorphism largely means a ‘non-disease-causing change with a frequency of 1% or higher in the population’ (den Dunnen and Antonarakis, 2001). We suggest that the term ‘variant’ is used when it is not certain whether change in nucleotide or the amino acid is a risk or a cause for disease, or a confirmed risk factor for disease. This term encompasses ‘polymorphism’ and ‘mutation’.

The DRD3 Ser9Gly variant, a potential risk factor for schizophrenia, obsessive–compulsive personality disorder, tardive dyskinesia and other disorders (de Leon et al., 2005; Keri et al., 2005; Light et al., 2006), was also recently found associated with increased risk for ET. This common Gly9 variant is probably a risk allele and may become pathogenic when internal or external environmental stress is present. Identification of variants that are associated with ET, especially if they lead to an abnormal gene expression or a change of amino acid sequence may exert
a combined or synergistic effect on susceptibility to disease (Siv Congress et al., 2000).

In future genetic studies it may be useful to subdivide ET into several subtypes based on whether it is present as a monosymptomatic disorder or whether it coexists with other neurological diseases, age at onset and other variables (Benito-Leon et al., 2006). For Mendelian inheritance ET pedigrees, regular mapping–cloning strategy including parametric linkage analysis and candidate gene screening may be employed, while non-Mendelian inheritance pedigrees or sporadic patients need to validate a gene–disease relationship through comparative analysis of linkage disequilibrium (LD) and disease-association patterns (Jonsson et al., 2003; Farrer, 2006). Although comparison of genotypes between ET patients and controls among different ethnicities may lead to the identification of disease-specific and ethnicity-specific genome variations, most insight might be gained by studying the functions of genes. Identification of the defective gene or risk allele will enable a better understanding and classification of ET, as well as genetic counselling and therapy of this disorder.

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References

Agundez JA, Jimenez-Jimenez FJ, Tejeda R, Bedesma MC, Ori-Pareja M, Gasalla T, et al. CYP2D6 polymorphism is not associated with essential tremor. Eur Neurol 1997; 38: 99–104.

Auer-Grumbach M, Strasser-Fuchs S, Wagner K, Kornner E, Fazekas F. Roussey-Ley syndrome is a phenotypic variant of Charcot-Marie-Tooth syndrome 1A associated with a duplication on chromosome 17p11.2. J Neurol Sci 1998; 154: 72–5.

Bain PG, Britton TC, Jenkins IH, Thompson PD, Rothwell JC, Thomas PK, et al. Tremor associated with benign IgM paraproteinaemic neuropathy. Brain 1996; 119: 789–99.

Baugham FA Jr, Higgins JV, Mann JD. Sex chromosome anomalies and essential tremor. Neurology 1973; 23: 623–5.

Benito-Leon J, Bermejo-Pareja F, Louis ED. Neurological Disorders in Central Spain (NEDICES) Study Group. Incidence of essential tremor in three elderly populations of central Spain. Neurology 2005; 64: 1721–5.

Benito-Leon J, Louis ED, Bermejo-Pareja F. Neurological Disorders in Central Spain (NEDICES) Study Group. Population-based case-control study of cognitive function in essential tremor. Neurology 2006a; 66: 69–74.

Benito-Leon J, Louis ED, Bermejo-Pareja F. Neurological Disorders in Central Spain Study Group. Elderly-onset essential tremor is associated with dementia. Neurology 2006b; 66: 1500–5.

Beom S, Cheong D, Torres G, Caron MG, Kim KM. Comparative studies of molecular mechanisms of dopamine D2 and D3 receptors for the activation of extracellular signal-regulated kinase. J Biol Chem 2004; 279: 28304–14.

Busenbark K, Barnes P, Lyons K, Ince D, Villagra F, Koller WC. Accuracy of reported family histories of essential tremor. Neurology 1996; 47: 264–5.
Keri S, Juhasz A, Rimanoczy A, Szekeres G, Kelemen O, Cimmer C, et al. Kaneko K, Igarashi S, Miyatake T, Tsuji S. Essential tremor and CAG repeats in the androgen receptor gene. Neurology 1993; 43: 1618–9.

Higgins JJ. Essential tremor: a heterogenous disorder. Mov Disord 2002; 17: 638–44.

Jacquemont S, Hagerman RJ, Leehey MA, Hall DA, Levine RA, Brunberg JA, et al. Penetrance of the fragile X-associated tremor/ataxia syndrome in a premutation carrier population. JAMA 2004; 291: 460–9.

Jankovic J, Baranyi M, Vizi ES. Change in the concentrations of amino acids and JNK3. Science 2000; 290: 1574–7.

Jankovic J, Beach J, Schwartz KS, Ondo W. Re-emergent tremor of Parkinson’s disease. J Neurol Neurosurg Psychiatry 1999; 67: 646–50.

Jankovic J, Beach J, Schwartz K, Hauser WA. How common is the most common adult movement disorder? Estimates of the prevalence of essential tremor throughout the world. Mov Disord 1998; 13: 5–10.

Louis ED, Ford B, W horrend J, Ottman R. Validity of family history data on essential tremor. Mov Disord 1999; 14: 456–61.

Louis ED, Ford B, Frucht S, Ottman R. Mild tremor in relatives of patients with essential tremor: what does this tell us about the penetrance of the disease? Arch Neurol 2001; 58: 1584–9.

Louis ED, Fernandez-Alvarez E, Dure LS 4th, Frucht S, Ford B. Association between male gender and pediatric essential tremor. Mov Disord 2006; 21: 1908–6.

Louis ED, Ottman R, Hauser WA. How common is essential tremor in 4 kindreds. Prospects for genetic mapping. Arch Neurol 1997; 54: 289–94.

Jankovic J, Schwartz KS, Ondo W. Re-emergent tremor of Parkinson’s disease. J Neurol Neurosurg Psychiatry 1999; 67: 646–50.

Jankovic J, Madisetty J, Vuong KD. Essential tremor among children. Pediatrics 2004; 114: 1203–5.

Jennette F, Funalot B, Jankovic J, Deng H, Lagarde JP, Lucotte G, et al. A functional variant of the dopamine D3 receptor is associated with risk and age-at-onset of essential tremor. Proc Natl Acad Sci USA 2006; 103: 10753–8.

Jonsson EG, Flyckt L, Burgert E, Crocq MA, Forslund K, Mattila-Evenden M, et al. Dopamine D3 receptor gene Ser9Gly variant and schizophrenia: association study and meta-analysis. Psychiatr Genet 2003; 13: 1–12.

Kaneko I, Igarashi S, Miyatake T, Tsuji S. Essential tremor and CAG repeats in the androgen receptor gene. Neurology 1993; 43: 1618–9.

Ker I, Juhasz A, Rimanoczy A, Szekeres G, Kelemen O, Cimmer C, et al. Habit learning and the genetics of the dopamine D3 receptor: evidence from patients with schizophrenia and healthy controls. Behav Neurosci 2005; 119: 687–93.

Kim JH, Cho YH, Kim JK, Park YG, Chung JW. Frequent sequence variation at the ETM2 locus and its association with sporadic essential tremor in Korea. Mov Disord 2005; 20: 1650–3.

Kovach MJ, Ruiz J, Kimonis K, Mueed S, Sinha S, Higgins C, et al. Genetic heterogeneity in autosomal dominant essential tremor. Genet Med 2001; 3: 197–9.

Kruger R, Vieira-Saecker AM, Kuhn W, Berg D, Muller T, Kuhn N, et al. Increased susceptibility to sporadic Parkinson’s disease by a certain combined ?-synuclein/apolipoprotein E genotype. Ann Neurol 1999; 45: 611–7.

La Spada AR, Wilson EM, Lubahn DB, Harding AE, Fischbeck KH. Androgen receptor gene mutations in X-linked spinal and bulbar muscular atrophy. Nature 1991; 352: 77–9.

Lacritz LH, Dewey R Jr, Giller C, Callum CM. Cognitive functioning in individuals with “benign” essential tremor. J Int Neuropsychol Soc 2002; 8: 125–9.

Leehey MA, Munhoz RP, Lang AE, Brunberg JA, Grigisby J, Greco C, et al. The fragile X premutation presenting as essential tremor. Arch Neurol 2003; 60: 117–21.

Light KJ, Joyce PR, Luty SE, Mulder RT, Frampton CM, Joyce LR, et al. Preliminary evidence for an association between a dopamine D3 receptor gene variant and obsessive-compulsive personality disorder in patients with major depression. Am J Med Genet B Neuropsychiatr Genet 2006; 141B: 409–13.

Lombardi WJ, Woolston DJ, Roberts JW, Gross RE. Cognitive deficits in patients with essential tremor. Neurology 2001; 57: 785–90.

Louis ED. Etiology of essential tremor: should we be searching for environmental causes? Mov Disord 2001; 16: 822–9.

Louis ED. Essential tremor. Lancet Neurol 2005; 4: 100–10.

Louis ED, Ottman R. Study of possible factors associated with age of onset in essential tremor. Mov Disord 2006; 21: 1980–6.

Louis ED, Frucht S, Hauser WA. How common is essential tremor? J Int Neuropsychol Soc 2003; 9: 10753–8.

Louis ED, Vonsattel JP, Honig LS, Ross GW, Lyons KE, Pahwa R. Neuropathologic findings in essential tremor. Neurology 2006; 66: 1756–9.

Lucking CB, Durr A, Bonifati V, Vaughan J, De Michele G, Gasser T, et al. Association between early-onset Parkinson’s disease and mutations in the parkin gene. N Engl J Med 2000; 342: 1560–7.

Lucotte G, Lagarde JP, Funalot B, Sokollot P. Linkage with the Ser9Gly DRD3 polymorphism in essential tremor families. Clin Genet 2006; 69: 437–40.

Ma S, Davis TL, Blair MA, Fang JY, Bradford Y, Haines JL, et al. Familial essential tremor with apparent autosomal dominant inheritance: should we also consider other inheritance modes? Mov Disord 2006; 21: 1368–74.

Mally J, Baranyi M, Vizi ES. Change in the concentrations of amino acids and Parkinson’s disease: influence of Rep1 on age at onset. Mov Disord 2006; 21: 1368–74.

Mizuta I, Nishimura M, Mizuta E, Yamashiki S, Ohta M, Kunoo S. Meta-analysis of alpha-synuclein/NACP polymorphism in Parkinson’s disease in Japan. J Neurol Neurosurg Psychiatry 2002; 73: 350.
Shahed J, Jankovic J. Exploring the relationship between essential tremor and Parkinson’s disease is associated with L-DOPA, homocysteine, and MTHFR genotype. Neurol Sci 2003; 207: 19–23.

Nicoliotti G, Annesi G, Carrideo S, Tomaino C, Di Costanzo A, Zappia M, et al. Familial essential tremor is not associated with SCA-12 mutation in southern Italy. Mov Disord 2002; 17: 837–8.

Ondo WG, Sutton L, Dat Vuong K, Lai D, Jankovic J. Hearing impairment in essential tremor. Neurology 2003; 61: 1093–7.

Pahwa R, Lyons KE, Wilkinson SB, Simpson RK Jr, Ondo WG, Tarsy D, et al. Long-term evaluation of deep brain stimulation of the thalamus. J Neurosurg 2006; 104: 506–12.

Pals P, Lincoln S, Manning J, Heckman M, Skipper L, Chen H, et al. Alpha-synuclein promoter confers susceptibility to Parkinson’s disease. Ann Neurrol 2004; 56: 591–5.

Pigullo S, Di Maria E, Marchese R, Bellone E, Gulli R, Scaglione C, et al. Essential tremor is not associated with alpha-synuclein gene haplotypes. Mov Disord 2003; 18: 822–6.

Pigullo S, De Luca A, Barone P, Marchese R, Bellone E, Colosimo A, et al. Mutation analysis of parkin gene by denaturing high-performance liquid chromatography (DHPLC) in essential tremor. Parkinsonism Relat Disord 2004; 10: 357–62.

Pollak RD, Pollak A, Idelson M, Bejarano-Achache I, Doron D, Blumenfeld A. The C677T mutation in the methylenetetrahydrofolate reductase (MTHFR) gene and vascular dementia. J Am Geriatr Soc 2000; 48: 664–8.

Rajput AH, Offord KP, Beard CM, Kurland LT, et al. Essential tremor in Rochester, Minnesota: a 45-year study. J Neurol Neurosurg Psychiatry 1984; 47: 466–70.

Rajput A, Robinson CA, Rajput R. Essential tremor course and disability: a clinicopathologic study of 20 cases. Neurology 2004; 62: 932–6.

Ryan MM, Jones HR Jr. CMTX mimicking childhood chronic inflammatory demyelinating neuropathy with tremor. Muscle Nerve 2005; 31: 528–30.

Sazci A, Ergul E, Basyilmek K. Association of the C677T and A1298C polymorphisms of methylenetetrahydrofolate reductase gene in patients with essential tremor in Turkey. Mov Disord 2004; 19: 1472–6.

Schwartz M, Grosbard D, Inzelberg R, Hocherman S. Dopamine-transporter imaging and visuo-motor testing in essential tremor, practical possibilities for detection of early stage Parkinson’s disease. Parkinsonism Relat Disord 2004; 10: 385–9.

Shahed J, Jankovic J. Exploring the relationship between essential tremor and Parkinson’s disease. Parkinsonism Relat Disord 2007; 13: 67–76.