

Brief Reports

Improvement of Isolated Myoclonus Phenotype in Myoclonus Dystonia after Pallidal Deep Brain Stimulation

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Abstract

Background: Myoclonus–dystonia is a condition that manifests predominantly as myoclonic jerks with focal dystonia. It is genetically heterogeneous with most mutations in the epsilon sarcoglycan gene (*SGCE*). In medically refractory cases, deep brain stimulation (DBS) has been shown to provide marked sustainable clinical improvement, especially in *SGCE*-positive patients. We present two patients with myoclonus–dystonia (one *SGCE* positive and the other *SGCE* negative) who have the isolated myoclonus phenotype and had DBS leads implanted in the bilateral globus pallidus internus (GPI).

Methods: We review their longitudinal Unified Myoclonus Rating Scale scores along with their DBS programming parameters and compare them with published cases in the literature.

Results: Both patients demonstrated complete amelioration of all aspects of myoclonus within 6–12 months after surgery. The patient with the *SGCE*-negative mutation responded just as well as the patient who was *SGCE* positive. High-frequency stimulation (130 Hz) with amplitudes greater than 2.5 V provided therapeutic benefit.

Discussion: This case series demonstrates that high frequency GPI-DBS is effective in treating isolated myoclonus in myoclonus–dystonia, regardless of the presence of *SGCE* mutation.

Keywords: Myoclonus–dystonia, deep brain stimulation, epsilon sarcoglycan gene

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Introduction

Myoclonus–dystonia (MD) is an autosomal dominant disorder that presents with myoclonic jerks and dystonia, although pure myoclonus may be the only manifestation.¹ Myoclonic jerks are the predominant feature, usually occurring in the upper body including the neck, shoulders, and arms, and are dramatically responsive to alcohol.² MD is genetically heterogeneous with most mutations or deletions in the epsilon sarcoglycan gene (*SGCE*).^{3–5} However, approximately 50% of MD patients are *SGCE* negative, although new genes and loci have been found in some pedigrees.^{3,4} Oftentimes oral medications do not provide optimal symptom benefit. Deep brain stimulation (DBS) has proven to be an efficient and

sustainable therapy for such patients, especially in those who are *SGCE* positive.^{6–18} We report on two patients with MD—one *SGCE* positive, the other *SGCE* negative—with isolated myoclonus phenotypes that were refractory to medications and successfully treated with bilateral globus pallidus internus deep brain stimulation (GPI-DBS). We show, through reviewing longitudinal Unified Myoclonus Rating Scale (UMRS) scores, that all aspects of myoclonus, regardless of its location on the body, disappear. This response was realized within 6 weeks of stimulation for both patients, despite their genetic heterogeneity. Furthermore, when combined with published cases in the established literature, there is a suggestion that high frequency with moderate to high voltage drives this therapeutic gain.

Methods

Patient 1

The first patient was a 30-year-old male who had developed jerking movements of the trunk and left arm in childhood. When he walked these movements worsened, and they dampened with running or leaning on his elbows. Genetic testing was positive for an *SGCE* gene mutation and he responded partially to both clonazepam (1 mg three times a day) as well as sodium oxybate (2–3 g daily), but he remained quite impaired. Alcohol (i.e., six shots of vodka) also provided complete symptomatic relief. Family history was negative. On physical examination (Video 1) there were frequent

myoclonic jerks of his torso and left arm when sitting at rest. Leaning forward attenuated the myoclonus briefly, but it would be exacerbated when walking or doing any other activity such as writing, typing, reaching for items, or eating. There was no myoclonus in his face, right arm, or lower limbs. Stimulation-induced myoclonus was present with claps. He showed no dystonic posturing at rest or with tasks such as writing. His presurgical rest, action, and stimulus UMRS subscores were 21, 38, and 2, respectively.

Patient 2

A 16 year-old female presented with a 3-year history of myoclonic jerks, predominantly on the right side. At the age of 13 years, she developed

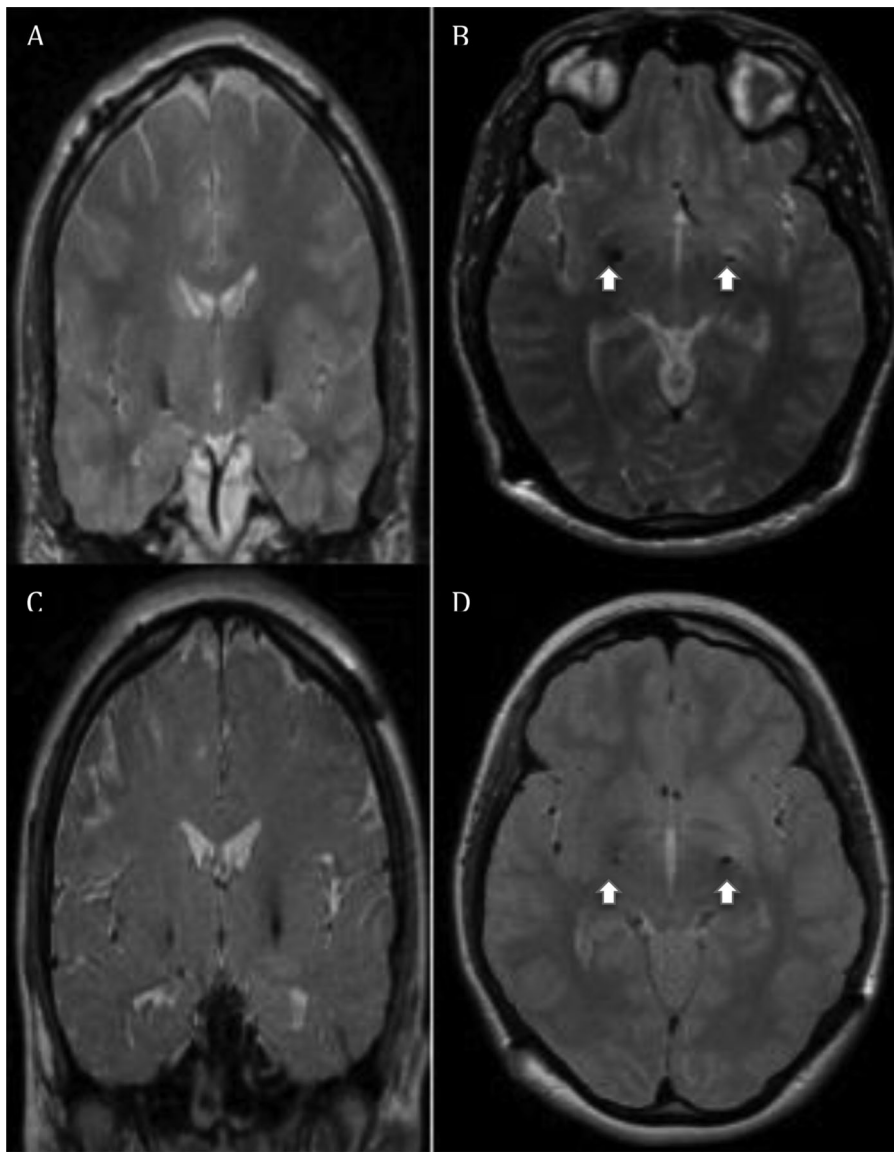


Figure 1. Postoperative T2-weighted Magnetic Images of Globus Pallidus Internus (GPi) Electrode Positioning with Coordinates in Anterior Commissure - Posterior Commissure Line Space. Patient 1: (A) coronal image of GPi electrodes; (B) axial image showing most ventral tip of electrodes (arrows) in GPi (Left: $X = -19.1, Y = +2.2, Z = -4.1$; Right: $X = 19.1, Y = 2.2, Z = -4.4$). Patient 2: (C) coronal image of GPi electrodes; (D) axial image showing most ventral tip of electrodes (arrows) in GPi (Left: $X = -20.1, Y = 1.5, Z = -3.2$; Right: $X = 19.3, Y = 2.0, Z = -3.5$).

myoclonic jerks of her right arm and forearm that interfered with writing and holding items. Over the subsequent years, her gait deteriorated because of the emergence of right leg myoclonus triggered by walking. Treatment with trihexyphenidyl (2 mg three times a day), clonazepam (0.5 mg daily), and botulinum toxin injections provided only modest benefit. Genetic testing was negative for *SGCE* mutations and brain magnetic resonance imaging (MRI) was normal. The family history was notable for tic disorder, which our patient also had in the past (i.e., eye blinking tics) before the onset of her condition. On physical examination (Video 2) while sitting at rest, there were myoclonic jerks present in her right arm and neck. There was no myoclonus on her left side. When she stood and walked, frequent action-induced myoclonus of the right leg produced an unsteady gait. Stimulation-induced myoclonus was absent. There was no dystonia in her face, neck, or limbs or when performing tasks such as writing. Her presurgical UMRS rest and action myoclonus subscores were 8 and 15, respectively.

Electrode implantation

Both patients underwent staged implantation of bilateral DBS electrodes (Medtronic 3389, Minneapolis, MN/USA) into the posteroventrolateral

GPI using a Leksell stereotactic frame and O-Arm guidance. The operative target was localized as 20 mm lateral to the midline, 2.5 mm anterior to the middle cerebral peduncle and 4 mm inferior to the commissural line. The target was then cross-correlated with the reformatted Schaltenbrand and Wahren atlas and with quantitative susceptibility mapping¹⁹ images showing the GPI. Intraoperative microelectrode recording provided further targeting refinement and postoperative MRI provided confirmation of electrode placement (Figure 1). The pulse generators (Activa SC, Medtronic, Inc) were implanted in the subclavicular region in both patients.

Postoperative programming commenced 4 weeks from placement of the second electrode and consisted of a monopolar review (pulse width [PW] 60 μ s, frequency 130 Hz) that determined the threshold for adverse effects such as muscle contractions and visual phosphenes. Contact(s) that provided visible myoclonus reduction together with unwanted side effects were chosen as the therapeutic contact(s). Amplitude was initially set at approximately 20% below the threshold for side effects, and incrementally increased over the subsequent weeks.

Longitudinal unblinded subscores of the UMRS (rest, action, stimulation-induced myoclonus) were evaluated for both patients.

Table 1. Pre- and Postoperative Unified Myoclonus Rating Scale Scores

	Rest	Action	Stimulus	% Change
Patient 1				
Preoperative	21	38	2	
Postoperative				
6 weeks	0	0	0	-100/-100/-100
7 month	2	4	0	-90/-89/-100
2 years	0	0	0	-100/-100/-100
3 years	0	0	0	-100/-100/-100
Patient 2				
Postoperative				
Preoperative	8	15	0	-
Postoperative				
1 week	1	5	0	-88/-67
1 month	0	2	0	-100/-87
2 month	0	0	0	-100/-100
3 month	0	0	0	-100/-100
4 month	0	2	0	-100/-87
5 month	0	1	0	-100/-93
6 month	0	2	0	-100/-87



Video 1. Pre- and Postoperative Examinations for Patient 1. In the pre-surgical state, the patient has persistent truncal and left arm myoclonus while sitting, during rest, and walking. Three years with bilateral globus pallidus internus deep brain stimulation there is no visible myoclonus.

Results

Both patients showed complete resolution of myoclonus with stimulation within 1 year of stimulation (Table 1). Considerable benefits were evident as early as 1 week (Patient 2), and by 4–6 weeks both rest and action myoclonus were substantially attenuated in both patients. Stimulus-sensitive myoclonus seen in Patient 1 disappeared. Writing improved for both patients along with feeding, typing, and walking. This response has been sustained in both patients, with no evidence of myoclonic jerks over 3 years in Patient 1 (Video 1) and 6 months for Patient 2 (Video 2).

High-frequency stimulation (130 Hz) was utilized in both patients. Dorsally located contact 2 was associated with robust myoclonus reduction. Right GPi therapeutic amplitudes ranged from 2.5 to 3.4 V

and PW 60–140 μ s, whereas left GPi therapeutic amplitudes ranged from 3.1 to 3.4 V and PW 60–90 μ s.

Patient 2 developed left shoulder rolling movements during the course of the programming that were consistent with tics, because they were stereotyped, suppressible, and associated with a premonitory urge. This tic responded to a longer PW. Patient 1 is no longer on medications for his myoclonus, and Patient 2 is being tapered off oral medications and has not required further botulinum toxin injections.

Discussion

DBS of the GPi and ventral intermediate nucleus (VIM) of the thalamus has emerged as a promising therapy for the treatment of refractory MD. Both patients developed isolated myoclonus that was



Video 2. Pre- and Postoperative Examinations for Patient 2. In the pre-surgical state, the patient has myoclonic jerks of the right arm at rest and when writing. Right leg myoclonus emerges when she walks. At 1 and 3 months with bilateral globus pallidus internus deep brain stimulation, there is no rest or action myoclonus.

Table 2. Summary of Published Cases of Pallidal Deep Brain Stimulation and SGCE-positive Myoclonus-Dystonia

Study	N	Age (years) [Range]	Disease Duration [range]	UMRS Preop/Postop/%Change	BFM preop/postop/%change	Contact	V	PW	Freq	Mean Followup (months)	Target		
Papuc et al. ⁶	1	31	27 years	NA	NA	NA	NA	NA	NA	NA	GPi(B)		
				Rest: 29	Rest: 9								
				Action: 55	Action: 16								
				Stimulus: 15	Stimulus: 5								
				Functional: 13	Functional: 3								
Uruha et al. ⁷	1	42	37 years	-70	14	4	-70	NA	NA	NA	GPi(B)		
Kurtis et al. ⁸	1	63	61 years	NA	40.5	22.5	-43	1	2.0	180	135	14	GPi (B)
Kuhn et al. ⁹	1	17	10 years	89	26	4.5	-83	1	3.4	90	130	9	GPi (B)
Gruber et al. ¹⁰	10	24-69	13-63	108.4 (mean)	36 (mean)	-66 (mean)	16.8 (mean)	-48 (mean)	NA	NA	NA	62	GPi/VIM (B)
Gif et al. ¹¹	1	8	7 years	69	13	-81	18.5	2.5	86	NA	NA	20	GPi (B)
	1	116	36	-73	16	16.5	-70	R C+;1-	4.7	60	130		
	2	76	20	-83	5.5	6.0	-70	L C+;1-	3.7	60	130		
	3	38	8	-74	4.5	5.0	-85	R C+;1-	3.3	60	130		
	4	70	6	-89	3.5	2.5	-86	L C+;2-	3.2	60	130		
	5	86	8	-93	3.5	2.5	-91	R C+;1-	2.0	60	130		
								L C+;2-	1.6	60	130		
								R C+;1-	3.3	60	130		
								L C+;1-	2.9	60	130		
								R C+;1-	3.4	60	130		
								L C+;1-	3.5	60	130		
Contarino et al. ¹³	5	18-50	NA	NA	NA	-23-89 (-72)	NA	-17-76 (-56)	NA	(72)	(130)	12	GPi (B)
	3	29-48	NA	46	8	-83	18	4	-78	90	130	27	GPi (B)
	2	70	58	-17	26	20	-23	R NA	L NA	120	130		
	3	100	0	-100	20	7	-65	R NA	L NA	60	130	12	GPi (B)
	1	70	0	-100	25.5	1	-96	L C+;1	2.4	60	130	120	GPi (B)
	2	86	1	-99	30.5	1	-97	R C+;1-	2.5	60	130	120	GPi (B)
	1	Rest: 21	Rest: 0	Rest: -100	NA	NA	NA	NA	2.4	60	130	36	GPi (B)
	1	Action: 38	Action: 0	Action: -100	NA	NA	NA	NA	2.5	60	130	36	GPi (B)
	1	Stimulus: 2	Stimulus: 0	Stimulus: -100	NA	NA	NA	NA	2.5	60	130	36	GPi (B)

Abbreviations: # - Active Contact(s); (B), Bilateral; BFM, xxx; C+, Case Positive; GPi, Globus Pallidus Internus; L, Left; NA, Not Available; PW, Pulse Width; R, Right; SGCE, Epsilon Sarcoglycan Gene; UMRS, Unified Myoclonus Rating Scale; VIM, Ventral Intermediate Nucleus.

Table 3. Summary of Published Cases of Pallidal Deep Brain Stimulation and SGCE-negative Myoclonus-Dystonia

Study	N	Age [range]	Disease Duration [range]	UMRS Preop/Postop/%change	BFM preop/postop/%change	Contact	V	PW	Freq	Mean Follow up (Months)	Target					
Sidiropoulos et al. ¹⁶	2	14	12 years	112/325	77/325	31.3%	10.5/120	4.5/120	57.1%	R C+;2- L C+;10-	3 3	60 60	130 130	4	GPI (B)	
				29/325	9/325	69%	NA	NA	R C+;2,3- L 11+10-	2.7 2	90 90	125 125	4.5	GPI (B)		
Kim et al. ¹⁷	1	37	29 years	82	45	11.8%	38.5	14.4%	R C+;0,1- L C+;0-1-	1.6 1.6	120 70	70	70	46	GPI (B)	
				93	45	51.6%	45	15.5	R C+;1,2,3- L C+;0,1,2-	2.3 2.2	150 120	120	120	120	46	GPI (B)
				39	39	58.1%	9	80%	R C+;1,2,3- L C+;0,1,2-	2.4 2.0	150 120	120	135	48	GPI VIM	
Gruber et al. ¹⁰	1	42	-	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Current Study	1	16	6years	Rest: 8	Rest: 0	Rest: -100	NA	NA	NA	NA	NA	140	130	6	GPI (B)	
				Action: 15	Action: 1	Action: -93	NA	NA	NA	90	130	6	GPI (B)			
				Stimulus: 0	Stimulus: 0	Stimulus: 0										

Abbreviations: (B), Bilateral; BFM, xxx; GPI, Globus Pallidus Internus; NA, Not Available; PW, Pulse Width; SGCE, Epsilon Sarcoglycan Gene; UMRS, Unified Myoclonus Rating Scale; VIM, Ventral Intermediate Nucleus.

refractory to medical therapy. A robust myoclonus response was appreciated as early as 1 week from initiation of stimulation. Furthermore, there was less variability in the time to significant motor response in our patients than DBS in primary generalized dystonia.²⁰

The dramatic results seen in Patient 1 are consistent with previously published data in SGCE-positive patients. Table 2 provides a summary of case reports and series of SGCE-positive patients treated with GPI-DBS. Myoclonus improvement ranged from 61% to 93% across the studies, with the majority of patients reported as having concomitant dystonia. Long-term sustained benefits from GPI-DBS were even reported at 10 years. SGCE-negative patients demonstrated less benefit (Table 3) with GPI-DBS, with myoclonus reduction ranging from 30% to 60%. Our SGCE-negative patient achieved substantial amelioration of all aspects of her myoclonus; however, the small number of reported SGCE-negative cases treated with DBS limits any speculation to a possible differential response to stimulation between SGCE-positive and SGCE-negative patients.

MD tends to produce myoclonic jerks and dystonia in the upper body. The lower limb predominant action myoclonus of Patient 2 is not only unique, but reveals the phenotypic variability of this rare condition.⁴ Furthermore, while a variable proportion (21–80%) of patients with MD have the SGCE mutation, recent identification of mutations in the RELN gene in a subset of SGCE-negative patients, reflects the genetic heterogeneity of this condition.²¹ Among the familial cohort found to have the RELN mutation, one patient was reported to have lower limb myoclonus.

Benefits across the published studies (Tables 2 and 3) were attained with high-frequency stimulation (range 120–185 Hz) and median amplitudes of 2.34–3.2 V for SGCE-negative and SGCE-positive patients, respectively. Although the mechanism underlying myoclonus remains unknown, neurophysiological data reveal that GPI neurons have a higher burst frequency with shorter pauses in MD than primary generalized dystonia.²² Pallidal local field potential recordings from MD patients also demonstrate oscillatory activity in the 3–15 Hz frequency band that synchronize with muscle activity.²³ Based on the growing evidence that striatopallidal network changes play a role in MD, we can hypothesize that a possible mechanism for the benefits achieved with GPI-DBS may be rooted in the regularization and desynchronization of abnormal neuronal activity and oscillations, paralleling similar suggested mechanisms of action in Parkinson’s disease²⁴ and dystonia.²⁵

In addition to striatopallidal dysfunction, cerebellar-thalamic network aberrancy^{26,27} via the parasagittal cerebellum, pontine nuclei, and posterior thalamus has also been implicated in SGCE-positive MD patients.^{28,29} The therapeutic benefit of thalamic DBS in treating myoclonus in MD patients¹⁰ might therefore be related to changes in this network. However, stimulation is usually in the ventral tier of the nucleus, and because of the overlap and lack of clarity of efferent fiber differentiation, it remains uncertain which network is being influenced with stimulation.

In summary, we present two cases of isolated myoclonus in MD, one SGCE positive and the other SGCE negative, both of which were effectively treated with bilateral pallidal stimulation. High-frequency stimulation with amplitudes >2.5 V were needed to reduce the

myoclonus. Benefits were realized within 1 month of initial programming and continue to be sustained in both patients.

References

- Gasser T. Inherited myoclonus–dystonia syndrome. *Adv Neurol* 1998;78:325–334.
- Furukawa Y, Rajput AH. Inherited myoclonus–dystonia: how many causative genes and clinical phenotypes? *Neurology* 2002;59:1130–1131. doi: 10.1212/WNL.59.8.1130.
- Ritz K, Gerrits MC, Foncke EM, et al. Myoclonus–dystonia: clinical and genetic evaluation of a large cohort. *J Neurol Neurosurg Psychiatry* 2009;80:653–658. doi: 10.1136/jnnp.2008.162099.
- Nardocci N, Zorzi G, Barzaghi C, et al. Myoclonus–dystonia syndrome: clinical presentation, disease course, and genetic features in 11 families. *Mov Disord* 2008;23:28–34. doi: 10.1002/mds.21715.
- Zimprich A, Grabowski M, Asmus F, et al. Mutations in the gene encoding epsilon-sarcoglycan cause myoclonus–dystonia syndrome. *Nat Genet* 2001;29:66–69. doi: 10.1038/ng709.
- Papuc E, Obszanska K, Rejdak K, Stelmasiak Z, Trojanowski T. Atypical symptomatology of myoclonus dystonia (DYT-11) with positive response to bilateral pallidal deep brain stimulation. *Mov Disord* 2014;29:E3. doi: 10.1002/mds.23783.
- Uruha A, Kimura K, Okiyama R. An Asian patient with myoclonus–dystonia (DYT11) responsive to deep brain stimulation of the globus pallidus internus. *Case Rep Neurol Med* 2014;2014:937095.
- Kurtis MM, San Luciano M, Yu Q, et al. Clinical and neurophysiological improvement of SGCE myoclonus–dystonia with GPI deep brain stimulation. *Clin Neurol Neurosurg* 2010;112:149–152. doi: 10.1016/j.clineuro.2009.10.001.
- Kuhn AA, Krause P, Lauritsch K, Zentner C, Brucke C, Schneider GH. Early surgical treatment in a case of myoclonus dystonia syndrome. *J Child Neurol* 2014;29:NP149–150. doi: 10.1177/0883073813513071.
- Gruber D, Kuhn AA, Schoenecker T, et al. Pallidal and thalamic deep brain stimulation in myoclonus–dystonia. *Mov Disord* 2010;25:1733–1743. doi: 10.1002/mds.23312.
- Cif L, Valente EM, Hemm S, et al. Deep brain stimulation in myoclonus–dystonia syndrome. *Mov Disord* 2004;19:724–727. doi: http://dx.doi.org/10.1002/mds.20030.
- Azoulay-Zyss J, Roze E, Welter ML, et al. Bilateral deep brain stimulation of the pallidum for myoclonus–dystonia due to epsilon-sarcoglycan mutations: a pilot study. *Arch Neurol* 2011;68:94–98. doi: 10.1001/archneurol.2010.338.
- Contarino MF, Foncke EM, Cath DC, Schuurman PR, Speelman JD, Tijssen MA. Effect of pallidal deep brain stimulation on psychiatric symptoms in myoclonus–dystonia due to epsilon-sarcoglycan mutations. *Arch Neurol* 2011;68:1087–1088; author reply 8–9. doi: 10.1001/archneurol.2011.180.
- Beukers RJ, Contarino MF, Speelman JD, Schuurman PR, Booij J, Tijssen MA. Deep brain stimulation of the pallidum is effective and might stabilize striatal D(2) receptor binding in myoclonus–dystonia. *Front Neurol* 2012;3:22. doi: 10.3389/fneur.2012.00022.
- Roze E, Vidailhet M, Hubsch C, Navarro S, Grabli D. Pallidal stimulation for myoclonus–dystonia: ten years' outcome in two patients. *Mov Disord* 2015;30:871–872. doi: 10.1002/mds.26215.
- Sidiropoulos C, Mestre T, Hutchison W, et al. Bilateral pallidal stimulation for sargoglycan epsilon negative myoclonus. *Parkinsonism Relat Disord* 2014;20:915–918. doi: 10.1016/j.parkreldis.2014.04.017.
- Kim JH, Na YC, Lee WH, Chang WS, Jung HH, Chang JW. Bilateral globus pallidus interna deep-brain stimulation in a patient with myoclonus–dystonia: a case report. *Neuromodulation* 2014;17:724–728.
- Rughani AI, Lozano AM. Surgical treatment of myoclonus dystonia syndrome. *Mov Disord* 2013;28:282–287. doi: 10.1002/mds.25326.
- Deistung A, Schafer A, Schweser F, Biedermann U, Turner R, Reichenbach JR. Toward in vivo histology: a comparison of quantitative susceptibility mapping (QSM) with magnitude-, phase-, and R2*-imaging at ultra-high magnetic field strength. *Neuroimage* 2013;65:299–314. doi: 10.1016/j.neuroimage.2012.09.055.
- Coubes P, Cif L, El Fertit H, et al. Electrical stimulation of the globus pallidus internus in patients with primary generalized dystonia: long-term results. *J Neurosurg* 2004;101:189–194. doi: 10.3171/jns.2004.101.2.0189.
- Groen JL, Ritz K, Jalalzadeh H, et al. RELN rare variants in myoclonus–dystonia. *Mov Disord* 2015;30:415–419. doi: 10.1002/mds.26070.
- Welter ML, Grabli D, Karachi C, et al. Pallidal activity in myoclonus dystonia correlates with motor signs. *Mov Disord* 2015;30:992–996. doi: 10.1002/mds.26244.
- Foncke EM, Bour LJ, Speelman JD, Koelman JH, Tijssen MA. Local field potentials and oscillatory activity of the internal globus pallidus in myoclonus–dystonia. *Mov Disord* 2007;22:369–376. doi: 10.1002/mds.21284.
- Kuhn AA, Kempf F, Brucke C, et al. High-frequency stimulation of the subthalamic nucleus suppresses oscillatory beta activity in patients with Parkinson's disease in parallel with improvement in motor performance. *J Neurosci* 2008;28:6165–6173. doi: 10.1523/JNEUROSCI.0282-08.2008.
- Montgomery EB, Jr. Effects of GPI stimulation on human thalamic neuronal activity. *Clin Neurophysiol* 2006;117:2691–2702. doi: 10.1016/j.clinph.2006.08.011.
- Hubsch C, Vidailhet M, Rivaud-Pechoux S, et al. Impaired saccadic adaptation in DYT11 dystonia. *J Neurol Neurosurg Psychiatry* 2011;82:1103–1106. doi: 10.1136/jnnp.2010.232793.
- Verghese J, Goldberg RF, Desnick RJ, et al. Myoclonus from selective dentate nucleus degeneration in type 3 Gaucher disease. *Arch Neurol* 2000;57:389–395. doi: 10.1001/archneur.57.3.389.
- Carbon M, Raymond D, Ozelius L, et al. Metabolic changes in DYT11 myoclonus–dystonia. *Neurology* 2013;80:385–391. doi: 10.1212/WNL.0b013e31827f0798.
- Tai CH, Yen RF, Lin CH, et al. Focal brain glucose hypermetabolism in myoclonus–dystonia syndrome caused by an epsilon-sarcoglycan gene mutation. *Parkinsonism Relat Disord* 2009;15:614–616. doi: 10.1016/j.parkreldis.2008.11.007.