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Original Article

Functional electrical stimulation enhances motor control in stroke rehabilitation

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Abstract: Objective: To investigate the effectiveness of functional electrical stimulation (FES) in enhancing motor control in stroke survivors. Methods: A retrospective study was conducted on clinical data from 150 stroke patients with lower-limb motor dysfunction, treated at Hunan Provincial People's Hospital from January 2023 to January 2024. Patients were divided into three groups: a control group (conventional rehabilitation), a CPN-FES group (conventional rehabilitation + calf muscle functional stimulation), and a TA-FES group (conventional rehabilitation + tibialis anterior functional stimulation). The data collected included F-wave latency and amplitude, H-reflex changes, lower-limb motor function, walking and balance abilities, mental status, and activities of daily living. The outcomes across the groups were compared to assess the efficacy of FES in improving motor control in stroke patients. Results: The study found that integrating electrical stimulation with early rehabilitation markedly enhanced stroke patients' recovery. After 8 weeks, improvements were observed in lower-limb motor function, walking and balance, cognitive status, and daily living activities. The CPN-FES group showed the greatest improvements, followed by the TA-FES group, while the control group demonstrated the least improvement. Additionally, FES therapy improved nerve conduction and reduced muscle spasticity, as evidenced by changes in F-wave and H-reflex measurements. Conclusion: The use of functional electrical stimulation in stroke rehabilitation appears to enhance motor control and improve functional outcomes. This approach merits further investigation in a clinical setting.

Keywords: F-wave, H-reflection, functional electrical stimulation (FES), stroke

Introduction

Stroke, or cerebrovascular accident, is characterized by sudden, focal impairment in brain function due to various vascular factors such as hemorrhage and ischemia, lasting for more than 24 hours [1, 2]. It is associated with high morbidity, mortality, and disability rates. Common clinical manifestations include deficits in postural control, muscle tone and strength, and balance function [3, 4]. Stroke remains a leading cause of long-term disability, significantly affecting the quality of life of survivors.

Both domestic and international studies have extensively explored the efficacy of functional electrical stimulation (FES) as a rehabilitative tool for stroke patients [5, 6]. FES has demonstrated potential in improving motor function and reducing disability in stroke survivors [7, 8]. However, the neurophysiological mechanisms underlying the effects of FES remain underexplored. Understanding these mechanisms is essential for optimizing FES protocols and maximizing its therapeutic benefits. Despite its potential, there is still limited knowledge regarding how FES interacts with neural pathways affected by stroke, which limits the development of more targeted and effective rehabilitation strategies. This study seeks to fill the gap by investigating how FES interacts with stroke-affected neural pathways, potentially facilitating the development of more targeted and effective rehabilitation strategies.

Materials and methods

Case selection

Data from 150 individuals with lower limb motor deficits following a cerebrovascular event, who underwent rehabilitation at Hunan Provincial People's Hospital between January 2023 to January 2024, were retrospectively analyzed. The study was approved by the Ethics Committee of Hunan Provincial People's Hospital.

Inclusion criteria: 1) Diagnosis of stroke based on the Fourth National Conference on Cerebrovascular Disease criteria; 2) Initial diagnosis confirmed by cranial CT or MRI, with disease duration between 1-12 months and stable condition; 3) All patients had foot drop and foot inversion on the affected side, and were willing to participate in rehabilitation treatment; 4) Modified Ashworth grade II or below for lower-limb spasticity; 5) Brunnstrom stage III or above for lower-limb motor recovery; 6) Ability to walk independently or with supervision for at least 10 meters without assistive devices. Exclusion Criteria: 1) Severe cardiopulmonary, hepatic, or renal impairment; 2) Severe cognitive or communication disorders; 3) Foot drop due to peripheral nerve injury; 4) Psychiatric disorders or the presence of cardiac pacemakers; 5) Non-continuous treatment or missing follow-up data.

Based on treatment records, cases were divided into a control group (conventional rehabilitation), a CPN-FES group (conventional rehabilitation + common peroneal nerve FES), and a TA-FES group (conventional rehabilitation + tibialis anterior FES).

Treatment method

Conventional rehabilitation: All selected patients underwent routine rehabilitation training on the basis of pharmacological treatment. Limb positioning: Patients were instructed in proper limb positioning (also known as anti-spasmodic positioning); Occupational therapy (OT): upper limb functional training guided by an occupational therapist; Physical therapy (PT): lower limb functional training guided by a physical therapist; Position changes: Training in transitioning between sitting and standing positions; Acupuncture: Routine acupuncture treatments aimed at promoting recovery; Daily functional training: Patients were guided by rehabilitation specialists in performing activities of daily living.

Guided by the therapist, the patients were trained to switch between sitting and standing positions, given routine acupuncture treatment, and instructed to carry out daily living ability training. The PT and OT trainings were conducted once a day for 40 minutes each time, five days a week, over a period of eight weeks. Acupuncture treatment was administered once daily, lasting 30 minutes per session, five times a week for eight weeks.

Functional electrical stimulation: FES was delivered using the GD-601 PAS neuromuscular biofeedback system (Japan). Stimulation parameters were: frequency at 40 Hz, pulse width of 50 μs, rise/fall time 1 s:1 s, current intensity 15-30 mA, and stimulation/rest intervals of 10 s. For the CPN-FES group, electrodes were placed near the exit point of the CPN at the posterior fibular head, targeting the deep peroneal nerve. In the TA-FES group, the cathode was placed over the motor point of the TA muscle, with the anode over the peroneus longus and brevis muscles, guided by EMG. All sessions were conducted by the same therapist once daily for 15 min, 5 days per week, over a period of 8 weeks.

Electrophysiological assessment

F-wave responses were recorded using the Dantec Keypoint EMG/evoked potential system (Denmark) in a 25°C temperature-controlled EMG lab. Stimulation was applied at the wrist (median nerve), and the M- and F-waves were automatically recorded. Gain was set to 0.05% for F-waves and 0.5 mV/div for M-waves. Stimulation intensity was increased until maximal M-wave amplitude was reached, then increased to 120% for F-wave assessment. Twenty consecutive stimulations were performed. Recorded parameters included F-wave occurrence rate, amplitude, F/M amplitude ratio, H-reflex latency, Hmax, Mmax, and Hmax/Mmax ratio.

Clinical assessment

Motor and functional status were assessed at baseline and after 8 weeks using: Active Range of Motion (AROM) and Fugl-Meyer Assessment of Lower Extremity (FMA-LE) for motor function; Functional Ambulation Categories (FAC) and Fugl-Meyer Balance Scale (FMB) for ambulation and balance; Mini-Mental State Examination (MMSE) for cognitive status; and Modified Barthel Index (MBI) for overall daily living ability.

Table 1. Comparison of the results of the general information of the three groups of patients

	CPN-FES Group (n=50)	TA-FES Group (n=50)	Control Group (n=50)	F/χ^2	p
Gender					
Male	34 (68%)	37 (74%)	35 (70%)	0.45	0.8
Female	16 (32%)	13 (26%)	15 (30%)		
Age (year)	51.28±10.24	52.32±11.32	51.58±10.56	0.79	0.45
Disease duration (month)	5.24±2.14	5.46±2.87	5.14±2.74	1.36	0.26
Etiology					
cerebral hemorrhage	32 (64%)	35 (70%)	33 (66%)	0.42	0.81
cerebral infarction	18 (36%)	15 (30%)	17 (34%)		
Hypertension	32 (64%)	30 (60%)	31 (62%)	0.41	0.52
Hemiplegic side (medicine)					
Left	27 (54%)	29 (58%)	22 (44)	2.08	0.35
Right	23 (46%)	21 (42%)	28 (56%)		
Ashworth classification					
0	40 (80%)	39 (78%)	41 (82%)	0.32	0.98
1	5 (10%)	5 (10%)	4 (8%)		
2	5 (10%)	6 (12%)	5 (10%)		
Brainstorm Staging					
3	36 (72%)	34 (68%)	37 (74%)	1.09	0.89
4	10 (20%)	12 (24%)	8 (16%)		
5/6	4 (8%)	4 (8%)	5 (10%)		

Observation indicators

Primary observation indicators included AROM and FMA-LE. Secondary observation indicators included FAC, FMB, MMSE, MBI, F-wave latency, F-wave amplitude, F/M amplitude ratio, H-reflex latency, Hmax/Mmax ratio.

Statistical analysis

Statistical analysis was performed using SPSS 26.0. For variables that followed a normal distribution, data were expressed as means ± standard deviations ($\overline{x}$±s). A one-way analysis of variance (ANOVA) followed with the least significant difference (LSD) t-test was conducted to compare differences among groups. The data were presented as proportions for count data, with the chi-squared test (χ^2) employed to assess the differences between groups prior to and following treatment. A significance level of 0.05 was set for statistical significance.

Results

General baseline data

No significant differences were observed among groups in terms of gender, age, disease duration, history of hypertension, stroke etiology, side of hemiparesis, or Ashworth and Brainstorm classifications (**Table 1**).

Lower limb motor function

Before treatment, no significant differences in AROM scores were observed among the three groups ($P > 0.05$). After 8 weeks of treatment, AROM scores significantly improved in all groups ($P < 0.001$). The CPN-FES group showed the highest improvement, followed by the TA-FES group, with the control group showing the least improvement. The differences between the groups were statistically significant ($P < 0.001$). Detailed results are shown in **Table 2**.

Fugl-Meyer assessment of lower extremity (FMA-LE) scores

Before treatment, there was no significant difference in FMA-LE scores among the three groups ($P > 0.05$). After 8 weeks of treatment, FMA-LE scores significantly improved in all three groups ($P < 0.001$). The CPN-FES group had the highest scores, followed by the TA-FES group, with the control group showing the least

Table 2. Comparasion of the AROM scores before and after treatment in each of three groups

	CPN-FES Group (n=50)	TA-FES Group (n=50)	Control Group (n=50)	F	P
Pre-treatment	6.86±1.74	7.04±1.69	6.94±1.55	2.54	0.18
Post-treatment	10.42±2.16[a,b]	9.34±2.43[a]	7.68±1.97	24.87	< 0.001
t	-11.57	-4.66	-4.02		
p	< 0.001	< 0.001	< 0.001		

[a]*p*, compared to control; [b]*p*, CPN-FES Group compared to TA-FES Group. AROM: Active Range of Motion.

Table 3. Comparison of FMA-LE scores before and after treatment in the three groups

	CPN-FES Group (n=50)	TA-FES Group (n=50)	Control Group (n=50)	F	P
Pre-treatment	18.30±5.2	18.72±5.64	18.26±4.95	1.76	0.17
Post-treatment	28.24±3.24[a,b]	24.58±4.39[a]	21.4±3.72	43.66	< 0.001
T	-11.57	-5.24	-4.49		
P	< 0.001	< 0.001	< 0.001		

[a]*p*, compared to control; [b]*p*, CPN-FES Group compared to TA-FES Group. FMA - LE: Fugl - Meyer Assessment of Lower Extremity.

Table 4. Comparison of the FAC before and after treatment in the three groups

	CPN-FES Group (n=50)	TA-FES Group (n=50)	Control Group (n=50)	F	P
Pre-treatment	2.20±0.54	2.14±0.46	2.22±0.41	0.67	0.52
Post-treatment	3.82±0.68[a]	3.58±0.72[a]	3.06±0.59	13.18	< 0.001
t	-12.34	-10.45	-8.65		
p	< 0.001	< 0.001	< 0.001		

[a]*p*, compared to control. FAC: Functional Ambulation Categories.

improvement. The differences among groups were statistically significant (P < 0.001). Detailed results are shown in **Table 3**.

Functional ambulation categories (FAC)

Before treatment, there were no significant differences in FAC scores between the three groups (P > 0.05). After 8 weeks of treatment, scores significantly increased in all groups (P < 0.001). The CPN-FES group and the TA-FES group showed higher scores than the control group (P < 0.001). However, no significant difference was found between the CPN-FES group and the TA-FES group (P > 0.05). Detailed results are shown in **Table 4**.

Fugl-Meyer balance (FMB) scores

Before treatment, there was no significant differences in FMB scores among the three groups (P > 0.05). After 8 weeks of treatment, FMB scores significantly improved in all groups (P < 0.001). The CPN-FES group had the highest scores, followed by the TA-FES group, with the control group showing the least improvement. The difference among the groups was statistically significant (P < 0.001), as shown in **Table 5**.

Mini-mental state examination (MMSE) scores

Before treatment, there was no significant difference in MMSE scores among the three groups (P > 0.05). After 8 weeks of treatment, MMSE scores significantly increased in all groups (P < 0.001). The CPN-FES group had the highest scores, followed by the TA-FES group, with the control group showing the least improvement. The difference among the groups was statistically significant (P < 0.001), as shown in **Table 6**.

Modified Barthel index (MBI)

Before treatment, there was no significant difference in MBI scores among the three groups (P > 0.05). After 8 weeks of treatment, MBI scores increased significantly in all groups (P < 0.001). The CPN-FES group had higher scores than both the TA-FES group and the control group (P < 0.001). No significant difference was

Table 5. Comparative analysis of FMB before and after treatment in the three groups

	CPN-FES Group (n=50)	TA-FES Group (n=50)	Control Group (n=50)	F	P
Pre-treatment	7.50±2.34	7.78±2.76	7.66±3.04	1.28	0.27
Post-treatment	12.18±1.79[a,b]	10.44±2.12[a]	8.70±1.75	19.52	< 0.001
T	-13.37	-5.86	-0.14		
P	< 0.001	< 0.001	0.89		

[a]*p*, compared to control; [b]*p*, CPN-FES Group compared to TA-FES Group. FMB: Fugl-Meyer Balance Scale.

Table 6. Comparison of the MMSE scores before and after treatment in the three groups

	CPN-FES Group (n=50)	TA-FES Group (n=50)	Control Group (n=50)	F	P
pre-treatment	22.80±4.83	23.02±4.92	22.88±4.71	2.49	0.08
post-treatment	28.80±1.27[a,b]	26.40±2.24[a]	23.64±3.46	30.57	< 0.001
t	-12.46	-7.38	-4.99		
p	< 0.001	< 0.001	< 0.001		

[a]*p*, compared to control; [b]*p*, CPN-FES Group compared to TA-FES Group. MMSE: Mini - Mental State Examination.

Table 7. Comparison of MBI before and after treatment in the three groups

	CPN-FES Group (n=50)	TA-FES Group (n=50)	Control Group (n=50)	F	P
pre-treatment	53.44±12.37	55.20±11.54	55.38±10.58	2.51	0.08
post-treatment	80.24±13.43[a,b]	74.70±12.15	70.50±14.62	8.254	< 0.001
t	-10.34	-9.59	-7.6		
p	< 0.001	< 0.001	< 0.001		

[a]*p*, compared to control; [b]*p*, CPN-FES Group compared to TA-FES Group. MBI: Modified Barthel Index.

found between the TA-FES group and the control group (P > 0.05), as shown in **Table 7**.

F-wave

Before treatment, there was no significant difference in F-wave incidence, latency, amplitude, and F/M amplitude ratio among the three groups (P > 0.05). After 8 weeks of treatment, significant differences were observed in F-wave latency, amplitude, and F/M amplitude ratio among the three groups (P < 0.001). The latency period was shortened, the amplitude was reduced, and the F/M amplitude ratio was reduced in the CPN-FES group and the TA-FES group, and the change was more obvious in the CPN-FES group. The control group showed smaller changes. There was no significant change in F-wave incidence among the three groups before and after treatment (P > 0.05), as shown in **Table 8**.

H-reflex latency

Before treatment, there were no significant differences in H-reflex latency and Hmax/Mmax among the three groups (P > 0.05). After 8 weeks of treatment, the H-reflex latency was significantly prolonged while Hmax/Mmax significantly decreased in all groups (P < 0.001). The CPN-FES group showed the greatest increase in latency and the most significant decrease in Hmax/Mmax, followed by the TA-FES group. The control group showed the least change. Detailed results are shown in **Table 9**.

Discussion

Electrical stimulation is a widely used rehabilitation therapy, with functional electrical stimulation (FES) being a form of neuromuscular electrical stimulation [9, 10]. This technique employs low-frequency electrical currents delivered to multiple muscle groups based on a predefined stimulation program. The goal is to induce muscular movements or to simulate normal voluntary muscle activity, thereby encouraging functional activities such as grasping, walking, and swallowing. FES has been widely recognized in the rehabilitation of upper limb function in stroke patients by the rehabili-

Table 8. Comparison of F-waves before and after treatment in the three groups

F-parameters	CPN-FES Group		TA-FES Group		Control Group	
	pre-treatment	post-treatment	pre-treatment	post-treatment	pre-treatment	post-treatment
Occurrence rate (%)	87.20±7.56	88.40±8.27	88.30±8.26	90.10±8.51	86.80±7.74	87.70±7.19
Incubation period (s)	24.24±1.48	20.46±1.25[a,b,c]	23.92±1.87	21.54±1.67[a,c]	24.68±1.94	24.22±1.74
F-wave amplitude (MA)	0.56±0.11	0.32±0.09[a,b,c]	0.58±0.12	0.45±0.07[a,c]	0.54±0.12	0.48±0.10[c]
F/M amplitude ratio (%)	7.54±2.16	5.28±1.14[a,b,c]	7.89±2.47	6.12±1.34[a,c]	7.32±2.63	6.78±1.25[c]

[a]*p*, compared to control; [b]*p*, CPN-FES Group compared to TA-FES Group. [c]*p*, The difference was statistically significant compared with the same group before treatment. F/M amplitude ratio: F - wave to M - wave amplitude ratio.

Table 9. Comparison of H-reflexes before and after treatment in the three groups

H reflectance parameter	CPN-FES Group		TA-FES Group		Control Group	
	pre-treatment	pre-treatment	pre-treatment	pre-treatment	pre-treatment	pre-treatment
Incubation period(s)	28.52±3.26	32.40±2.51[a,b,c]	27.87±3.69	30.14±2.84[a,c]	28.14±3.85	29.43±3.08
Hmax/Mmax (%)	0.77±0.14	0.38±0.07[a,b,c]	0.74±0.18	0.52±0.09[a,c]	0.76±0.16	0.63±0.11[c]

[a]*p*, compared to control; [b]*p*, CPN-FES Group compared to TA-FES Group. [c]*p*, The difference was statistically significant compared with the same group before treatment. Hmax/Mmax: Maximum H - reflex to Maximum M - wave ratio.

tation medicine community [11]. FES, as a novel therapeutic technique, is increasingly applied in research focusing on the rehabilitation of upper limb motor function in stroke patients. However, studies on its effects on motor control function remain limited. In this study, FES was employed to regulate motor control capacity and treatment effects in 150 stroke patients. Following eight weeks of treatment, results demonstrated significant improvements in all outcome measures for the TA-FES, CPN-FES, and control groups compared to the pre-treatment levels. Furthermore, both the TA-FES and CPN-FES groups exhibited superior outcomes in comparison to the control group. These findings suggest that FES can effectively enhance motor control and improve the quality of life in stroke patients.

The F-wave, first proposed by Dr. Charles H. Best in 1950, is considered a late muscle response occurring in the absence of voluntary muscle activation [12]. It is believed to be elicited by the stimulation of peripheral nerves. When a peripheral nerve is subjected to intensive stimulation, a substantial downstream-conducting compound muscle action potential, known as the M-wave, is generated. Concurrently, a modest muscle response potential, the F-wave, can be observed on the EMG following the M-wave. It is widely accepted in contemporary research that the F-wave can be employed as an index to evaluate the excitability of motor cells in the anterior horn of the spinal cord. Commonly utilized F-wave parameters include amplitude, F/M amplitude ratio, frequency of F-wave appearance, F-wave conduction velocity and latency [13-16]. As stroke progresses, the F wave in the affected limb is prolonged, and the amplitude increases. This study demonstrates that patients in the TA-FES and CPN-FES groups exhibited shorter F-wave latencies and reduced wave amplitudes after treatment. These findings indicate that FES treatment may have a more favorable impact on these patients.

The H-reflex was initially conceptualized by Hoffmann in 1918 as the reflex response of the triceps muscle in the lower leg evoked by subthreshold stimulation of the posterior tibia nerve. This concept was further developed by Maglardery and McDougal in the 1950s, who demonstrated that the H-reflex can be utilized to assess the excitability of α-moto neurons in the anterior horn of the spinal cord. Additionally, it offers insights into the functional status of both sensory and motor fibers along the conduction pathway. The H-reflex is an electromyographic assessment that quantifies neuromuscular junction excitability, with key metrics including the H-reflex wave amplitude, the Hmax/Mmax ratio, and the threshold ratio [17-19]. Similar to the development of the F-wave, some researchers have validated the reliability of the H-reflex in clinical studies investigating spasticity in stroke patients. Recently, however, the H-reflex has been employed less frequently in the assessment of post-stroke limb spasticity compared to the F-wave. Internationally, some studies have proposed that Hmax/Mmax ratio can serve as an indirect measure of motor neuron excitability, reflecting the activation of motor neurons [20-22]. Repeated evaluations of the H-reflex in hemiplegic patients with cerebrovascular disease have demonstrated that Hmax/Mmax ratio reliably assesses myoclonic spasticity [23, 24]. Furthermore, the Hmax/Mmax ratio is sensitive in monitoring myoclonic spasticity over time in hemiplegic patients. In cases of central nervous system damage and upper motor neuron impairment, an increase in the Hmax/Mmax ratio indicates heightened excitability of central motor neurons [25-27]. This study revealed no discernible differences in latency among the three groups prior to treatment. However, following treatment, latency increased, and the Hmax/Mmax ratio declined. These findings suggest that while stroke-induced central nervous system damage and the absence of upper motor neuron inhibition increase spinal cord excitability and monosynaptic reflexes, FES treatment may help alleviate muscular spasticity, supporting recovery of walking ability.

Pathological walking patterns following a cerebrovascular accident are attributable to a variety of factors, including lower limb muscle weakness, increased muscle tone, altered proprioception, and the development of joint deformities. Clinical assessment often show that restricted ankle ROM has the most significant impact on an individual's ability to walk [28, 29]. This pilot study compared the contraction of the TA and peroneus longus (long) and brevis muscles (short) through FES of the CPN with the direct stimulation of the TA motor point by FES, aiming to evaluate the effect of stimulating the nerve and corresponding muscles on the patient's walking ability. The results from eight weeks of intervention showed significant improvements in active ankle dorsiflexion for all three groups. The most notable improvement was observed in the TA-FES and CPN-FES groups, which received an additional treatment session. These groups demonstrated the greatest improvement in ankle dorsiflexion angle compared to the control group.

The Fugl-Meyer Lower Extremity Motor Function Assessment Scale (FMA-LE) is a widely employed tool for evaluating motor functions following a stroke. A study by Edgar et al. demonstrated the reliability of the FMA-LE in assessing post-stroke motor function [30]. In the current study, the FMA-LE scores for all three groups exhibited statistically significant improvements, with greater improvement observed in the CPN-FES group than in the TA-FES group. The TA-FES group, however, was more effective in improving flexor and extensor co-movement, as well as activities involving coordinated, movement of the hip, knee, and ankle joints. These results indicate that FES stimulation was particularly beneficial for improving lower limb motor function in the patients.

Furthermore, the ability to walk and maintain balance, cognitive status, and overall functional capability are critical factors in determining the potential for independent living following a stroke. Stroke rehabilitation programs are designed to improve walking ability, focusing on factors such as walking speed, walking endurance, and body balance. FAC serves as a standardized assessment of gait ability [31-33], while ADL is the most crucial prognostic factor for functional independence following acute stroke [34, 35]. Additionally, cognitive dysfunction can significantly affect the rehabilitation process for stroke patients [35-37]. The results of the present study indicate that patients showed improvements in walking ability, balance, mental status, and overall functional capacity following treatment. Although this study demonstrates the positive effects of FES on patients with lower-limb motor dysfunction following a stroke, it has certain limitations. Future studies should consider adopting a multi-center, randomized and double-blind design, conducting long-term follow-ups, individualizing FES parameters, assessing patient compliance, controlling for potential confounding factors, and exploring the underlying mechanisms of treatment. These steps will enhance the scientific rigor and credibility of the findings.

Conclusion

This study evaluated the effectiveness of Functional Electrical Stimulation (FES) on motor control recovery in stroke patients. Eight weeks of FES significantly improved motor function, walking and balance abilities, cognitive status, and daily living activities of stroke patients. The CPN-FES group showed the most significant improvement, followed by the TA-FES group, with the control group exhibiting the least progress. FES also contributed to improved nerve conduction and a reduction in muscle spasticity. In conclusion, FES has the potential to enhance rehabilitation outcomes in stroke patients.

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Disclosure of conflict of interest

None.

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