Am J Transl Res 2025;17(2):1114-1124
www.ajtr.org /ISSN:1943-8141/AJTR0160997

Original Article

Differential effects of low- and high-frequency sacral neuromodulation on urinary symptoms: high-frequency improves Qmax, low-frequency enhances bladder capacity

Yuansong Xiao*, Hui Zhang*, Haoyu Yuan, Xiaoyu Lin, Chenglin Yang, Jixian Gao

*Department of Urology, PLA General Hospital of Southern Theater Command, Guangzhou 510010, Guangdong, China. *Equal contributors and co-first authors.*

Received October 8, 2024; Accepted December 27, 2024; Epub February 15, 2025; Published February 28, 2025

Abstract: Objective: To compare the efficacy, safety, and patient satisfaction between low- and high-frequency sacral neuromodulation (SNM) in patients undergoing SNM. Methods: This retrospective study included 263 patients treated between January 2016 and December 2022 at PLA General Hospital of Southern Theater Command. Patients received either low-frequency (≤ 16 Hz) or high-frequency (> 16 Hz) SNM. Urodynamic outcomes, quality of life, adverse events, and patient satisfaction were assessed pre- and post-treatment. Results: Of the cohort, 128 patients received low-frequency and 135 received high-frequency stimulation. Post-treatment, the high-frequency group showed a significant improvement in maximum urinary flow rate (Qmax) and detrusor contractility compared to the low-frequency group. In contrast, the low-frequency group exhibited greater increases in maximum bladder capacity. Both groups demonstrated significant reductions in urination difficulty and waiting times, with the high-frequency group achieving more pronounced improvements. Quality of life scores and adverse event rates were similar across both groups. High patient satisfaction was noted in both groups, with no significant difference in overall satisfaction rates ($P = 0.404$). Correlation analysis indicated significant relationships between stimulation frequency and various urodynamic parameters, with higher frequencies generally associated with better urodynamic outcomes. Conclusion: Both low- and high-frequency SNM improve urinary symptoms and quality of life, with high-frequency showing better urodynamic outcomes in Qmax and detrusor contractility, while low-frequency enhances bladder capacity. Both treatments are safe and highly satisfactory to patients.

Keywords: Sacral neuromodulation, low-frequency stimulation, high-frequency stimulation, overactive bladder, urodynamic outcomes, patient satisfaction

Introduction

The prevalence of urinary dysfunctions, particularly overactive bladder (OAB) and related disorders, poses significant challenges to individuals worldwide, affecting both quality of life and daily functioning [1]. Epidemiologically, OAB impacts approximately 10-15% of the global population, with incidence rates rising in individuals over the age of 40 and a higher prevalence among women [2]. Common outcomes include urinary incontinence, urgency, nocturia, and increased micturition frequency, all of which are socially and emotionally debilitating and contribute to substantial healthcare costs due to ongoing management and treatment [3].

OAB can be classified by etiology into neurogenic and idiopathic types, with various pathophysiological mechanisms in volved, including detrusor overactivity, impaired neural control, and altered sensory feedback from the bladder [4].

Sacral neuromodulation (SNM) has emerged as a cornerstone therapeutic modality for refractory urinary dysfunctions, providing an innovative alternative to pharmacological therapies [5]. Initially used in the management of certain neurogenic bladder disorders, SNM involves modulating neural pathways to rebalance detrusor-sphincter coordination and bladder storage capabilities [6]. However, despite the recognized efficacy of SNM in clinical prac-

https://doi.org/10.62347/IGEX6196

tice, the effects of varying stimulation frequencies on patient outcomes remain poorly understood [7]. Current knowledge suggests differential impacts on detrusor contractility and bladder sensory pathways, yet precise mechanisms remain ambiguous [8].

Existing research focuses predominantly on the clinical efficacy and adverse effect profiles associated with SNM, often neglecting the specific urodynamic changes prompted by different stimulation frequencies [9]. While some studies have suggested that low- versus high-frequency modulation may selectively influence bladder storage and voiding phases, comprehensive data quantifying these effects are scarce [10]. Furthermore, it is unclear how frequency-dependent urodynamic changes translate into subjective improvements in patient quality of life and satisfaction, thus limiting the optimization of treatment regimens [11]. These gaps highlight a critical need for systematic investigations that elucidate the full spectrum of physiological changes associated with varying SNM frequencies [12].

Addressing these unknown aspects is of vital importance for enhancing the clinical management of urinary dysfunctions [13]. By examining the urodynamic characteristics modulated by different frequencies, clinicians can better tailor interventions to meet individual patient needs, potentially improving both therapeutic outcomes and quality of life [14]. Innovative approaches, such as controlled trials that concurrently assess objective urodynamic parameters alongside subjective quality of life measures, offer the potential to unravel these complexities [15]. Furthermore, technological advancements in urodynamic testing provide an opportunity to explore underrepresented parameters in current orthopedic and urological literature [16]. This study endeavors to address these gaps by systematically evaluating urodynamic parameters using different frequencies of SNM. By comparing low-frequency and high-frequency modulation, we aim to illuminate the distinct physiological adaptations that occur within the urinary tract.

Methods and subjects

Case selection

From January 2016 to December 2023, a total of 263 patients who underwent successful SNM therapy and two-stage sacral nerve stimulator implantation at PLA General Hospital of Southern Theater Command were enrolled. The patients were divided into two groups: the low-frequency group ($f \leq 16$ Hz) and the high-frequency group ($f > 16$ Hz). This study was approved by the Ethics Committee of PLA General Hospital of Southern Theater Command.

Eligibility criteria: ① Absolute indications for SNM included refractory OAB, idiopathic urinary retention, and others. Relative indications included neurogenic bladder, among others [17, 18]; ② Conservative treatment either ineffective or poorly tolerated; ③ No contraindications to SNM; ④ Adults aged 18 years or older; ⑤ Successful phase I testing, followed by phase II surgery.

Exclusion criteria: ① Mental and psychological disorders; ② Organic lesions of the lower urinary tract; ③ Presence of any active infection; ④ Under 18 years of age; ⑤ Physical limitations preventing surgery tolerance; ⑥ Severe obesity or extreme thinness.

Intervening methods

Preoperative examinations, including lumbosacral spinal Magnetic Resonance Imaging (MRI), urodynamic examination, and voiding diary, were performed to evaluate whether the patient was suitable for SNM therapy.

Under X-ray guidance, a puncture needle was inserted into the S3 vertebra, and the test stimulation stie was repeatedly adjusted. Once the best S3 nerve response was achieved, the electrode was implanted, and the electrode wire was extended outside the body to initiate the phase I test, which generally lasted no more than 30 days. During the phase I test, the frequency, pulse width, and voltage of the stimulation were adjusted, and the micturition diary was recorded to fine-tune the stimulation parameter based on both subjective and objective patient data. For the low-frequency group ($f \leq 16$ Hz), the initial stimulation frequency was set to ≤ 16 Hz, with adjustments made based on patient response to achieve optimal symptom improvement. For the high-frequency group ($f > 16$ Hz), the initial stimulation frequency was set to > 16 Hz, with similar adjustments made to achieve the best possible outcomes. If symptoms improved by more than 50%, the second stage of permanent sacral nerve stimulator implantation was performed after full communication with the patient. Preoperative urodynamic study and surgery were performed by the same doctor. All patients underwent detailed clinical evaluation before operation.

The first stage test treatment lasted for 2-6 weeks, and the second-stage operation was performed after successful test treatment and selection of the optimal stimulation parameters.

Data collection

General patient information, including age, gender, body mass index (BMI), and comorbidities such as diabetes and hypertension, was retrieved from the medical record system. Statistical analysis was performed to evaluate the efficacy of treatment and the incidence of postoperative adverse reactions.

Outcome measurements

The primary outcome was urodynamic parameters, and the secondary outcomes included scores for urination difficulty, waiting time, the Short-Form 36 (SF-36) quality of life scale and patient satisfaction.

Urodynamic tests were conducted before and after treatment using the Weist urodynamics testing instrument. The following indicators were primarily measured: maximum urinary flow rate (Qmax), maximum bladder capacity, residual urine volume, abdominal pressure during urination, detrusor contractility, coordination of the external sphincter, bladder compliance, frequency of micturition, and bladder sensation.

Patients rated their urination difficulty and waiting time on a scale from 0 to 10 before and after treatment, where 0 indicates no urination difficulty or waiting, and 10 indicates extreme urination difficulty and waiting.

The SF-36 Quality of Life Scale was used to assess multiple aspects of patient quality of life after treatment, including somatization, emotional management, role play, cognitive function, and social functioning. Higher scores reflects a better quality of life. The scale demonstrated a Cronbach's alpha coefficient of 0.814 [19].

Patient satisfaction was assessed using a hospital-developed patient satisfaction questionnaire. Patient satisfaction levels were categorized into three grades: completely satisfied, partially satisfied, and dissatisfied. The total score is 100 points, with higher scores indicating higher patient satisfaction.

Statistical methods

Data analysis was performed using SPSS 27.0 statistical software (SPSS Inc., Chicago, IL, USA). Categorical variables were presented as [n (%)], and chi-square test was adopted for analysis. The Shapiro-Wilk test was used to assess the normal distribution of continuous variables. Normally distributed continuous variables were presented as (Mean ± SD) and analyzed using the independent samples t-test. The relationship between urodynamic parameters and SNM frequency was analyzed using Spearman correlation analysis. A two-sided $P < 0.05$ was considered statistically significant.

Results

Basic information of enrolled patients

In this study, we evaluated the urodynamic parameters in patients receiving different frequencies of SNM therapy. The cohort consisted of 128 patients in the low-frequency stimulation group and 135 patients in the high-frequency stimulation group (**Table 1**). There were no significant differences in age, gender, BMI, hypertension, diabetes, smoking or alcohol consumption history, or the presence of neurogenic conditions between the two groups (all $P > 0.05$).

Comparison of urodynamic parameters between the low frequency group and high frequency group

In this study, we compared video urodynamic parameters between patients receiving low- and high-frequency SNM (**Table 2**). Prior to treatment, there were no significant differences in the Qmax, maximum bladder capacity, residual urine volume, abdominal pressure to urinate, detrusor contractility, or coordination of the external sphincter between the two

Table 1. Comparison of baseline data between the low- and high-frequency group

Parameter	Low frequency (n = 128)	High frequency (n = 135)	t/χ^2	P
Age (years)	54.79 ± 8.97	56.33 ± 8.41	1.440	0.151
Gender (%)			0.414	0.520
Male	67 (52.34%)	76 (56.30%)		
Female	61 (47.66%)	59 (43.70%)		
BMI (kg/m^2)	24.28 ± 2.38	24.45 ± 2.46	0.584	0.560
Hypertension (%)	32 (25.00%)	27 (20.00%)	0.944	0.331
Diabetes (%)	27 (21.09%)	24 (17.78%)	0.462	0.497
Smoking history (%)	26 (20.31%)	30 (22.22%)	0.143	0.705
Alcohol consumption history (%)	33 (25.78%)	39 (28.89%)	0.319	0.572
Neurogenic (%)	72 (56.25%)	88 (65.19%)	2.202	0.138

BMI: Body mass index.

Table 2. Comparison of urodynamic parameters between the low- and high-frequency group

Parameter	Time	Low frequency (n = 128)	High frequency (n = 135)	t/χ^2	P
Maximum urinary flow rate (Qmax) (ml/s)	Before treatment	9.33 ± 3.37	9.04 ± 3.07	0.741	0.459
	After treatment	10.14 ± 4.26	11.35 ± 4.15	2.328	0.021
t		1.687	5.199		
P		0.093	< 0.001		
Maximum bladder capacity (ml)	Before treatment	235.46 ± 48.91	246.55 ± 53.12	1.758	0.080
	After treatment	288.23 ± 75.45	259.14 ± 70.24	3.238	0.001
t		6.640	1.661		
P		< 0.001	0.098		
Residual urine volume of bladder (ml)	Before treatment	170.09 ± 84.86	178.23 ± 89.65	0.755	0.451
	After treatment	157.83 ± 66.25	141.46 ± 48.14	2.282	0.023
t		1.288	4.199		
P		0.199	< 0.001		
Abdominal pressure to urinate (Normal, %)	Before treatment	56 (43.75%)	58 (42.96%)	0.017	0.898
	After treatment	61 (47.66%)	62 (45.93%)	0.079	0.779
χ^2		0.394	0.240		
P		0.530	0.624		
Detrusor contractility (Normal, %)	Before treatment	32 (25.00%)	36 (26.67%)	0.095	0.758
	After treatment	41 (32.03%)	60 (44.44%)	4.280	0.039
χ^2		1.552	9.310		
P		0.213	0.002		
Coordination of the external sphincter (%)	Before treatment	50 (39.06%)	48 (35.56%)	0.346	0.557
	After treatment	55 (42.97%)	75 (55.56%)	4.164	0.041
χ^2		0.404	10.886		
P		0.525	0.001		

groups (all $P > 0.05$). However, post-treatment, significant improvements were observed in Qmax, residual urine volume, detrusor contractility, and coordination of the external sphincter in the high-frequency group compared to the low-frequency group (all $P < 0.05$). For maximum bladder capacity, significant improvement was observed in the low-frequency group post-treatment, surpassing the high-frequency group ($P < 0.05$). No significant changes were noted in abdominal pressure to urinate after treatment in either group ($P > 0.05$).

Table 3. Comparison of bladder function between the low- and high-frequency group

Parameter	Time	Low frequency (n = 128)	High frequency (n = 135)	t/χ^2	P
Bladder compliance (Normal, %)	Before treatment	64 (50.00%)	70 (51.85%)	0.090	0.764
	After treatment	92 (71.88%)	80 (59.26%)	4.621	0.032
χ^2		11.176	1.500		
P		0.001	0.221		
Frequency of Micturition (times/day)	Before treatment	8.25 ± 2.01	8.12 ± 2.06	0.518	0.605
	After treatment	6.47 ± 1.15	6.24 ± 1.23	1.496	0.136
t		8.696	9.104		
P		< 0.001	< 0.001		
Bladder sensation (Normal, %)	Before treatment	39 (30.47%)	47 (34.81%)	0.564	0.453
	After treatment	59 (46.09%)	65 (48.15%)	0.111	0.739
χ^2		6.613	4.943		
P		0.010	0.026		

Table 4. Comparison of treatment efficacy between the low- and high-frequency group

Parameter	Complete remission	Partial remission	No remission	Response rate
Low frequency (n = 128)	68 (53.13%)	54 (42.18%)	6 (4.69%)	122 (95.31%)
High frequency (n = 135)	78 (57.78%)	46 (34.07%)	11 (8.15%)	124 (91.85%)
χ^2				1.301
P				0.254

Comparison of bladder function between the low frequency group and high frequency group

In the analysis of bladder function between patients undergoing low- and high-frequency SNM, bladder compliance showed a marked improvement in the low-frequency group after treatment (P < 0.05) (**Table 3**). In contrast, the post-treatment compliance of the high-frequency group did not show a significant change compared to baseline (P > 0.05). The frequency of micturition decreased significantly in both groups after treatment (both P < 0.001). A notable post-treatment improvement was observed in both groups in terms of bladder sensation (all P < 0.05).

Comparison of treatment efficacy between the low frequency group and high frequency group

The response rate, including both complete and partial remission (**Table 4**), was high in both treatment groups: 95.31% in the low-frequency group and 91.85% in the high-frequency group, with no significant difference between the two groups (P > 0.05). Overall, both treatment frequencies demonstrated high efficacy, with similar response rates.

Comparison of urination difficulty and degree of waiting between the low frequency group and high frequency group

Significant improvements in urination difficulty were observed post-treatment in both groups, with the high-frequency group showing a more pronounced improvement (P < 0.05) (**Table 5**). The degree of waiting scores also showed substantial improvement, with the high-frequency group achieving a more significant reduction (P < 0.001). Overall, both treatment protocols effectively reduced urination difficulty and the degree of waiting, with the high-frequency group demonstrating better efficacy.

Comparison of quality of life between the low frequency group and high frequency group

No statistically significant differences were observed between the low-frequency and high-frequency groups in terms of quality of life across all evaluated parameters (P > 0.05) (**Table 6**). Overall, both groups exhibited simi-

Table 5. Comparison of urination difficulty and degree of waiting between the low- and high-frequency group

Parameter	Time	Low frequency (n = 128)	High frequency (n = 135)	T	P
Urination difficulty	Before treatment	8.25 ± 1.03	8.14 ± 1.11	0.825	0.410
	After treatment	5.15 ± 1.23	4.75 ± 1.06	2.852	0.005
t		21.861	25.663		
P		< 0.001	< 0.001		
Degree of waiting	Before treatment	8.13 ± 1.21	7.96 ± 1.47	1.018	0.310
	After treatment	4.85 ± 0.87	4.24 ± 0.76	6.105	< 0.001
t		24.900	26.119		
P		< 0.001	< 0.001		

Table 6. Comparison of quality of life between the low- and high-frequency group

Parameter	Low frequency (n = 128)	High frequency (n = 135)	t	P
Somatization	73.83 ± 4.01	74.32 ± 3.39	1.085	0.279
Emotion management	73.68 ± 4.38	74.04 ± 5.06	0.618	0.537
Role play	78.75 ± 6.13	79.39 ± 5.76	0.871	0.385
Cognitive function	78.91 ± 5.11	79.73 ± 5.54	1.250	0.212
Return to social function	79.65 ± 7.38	80.07 ± 4.02	0.568	0.570

Table 7. Comparison of adverse events between the low- and high-frequency group

Parameter	Low frequency (n = 128)	High frequency (n = 135)	χ^2	P
UTI Episodes	5 (3.91%)	8 (5.93%)	0.570	0.450
Hematuria	6 (4.69%)	3 (2.22%)	0.577	0.447
Other Side Effects	3 (2.34%)	2 (1.48%)	0.004	0.952
Treatment Discontinuation (%)	2 (1.56%)	3 (2.22%)	0.000	1.000

UTI: Urinary Tract Infection.

Table 8. Comparison of patient satisfaction between the low- and high-frequency group

Parameter	Full satisfaction	Partial satisfaction	Dissatisfaction	Overall satisfaction rate
Low frequency (n = 128)	98 (76.57%)	26 (20.31%)	4 (3.12%)	124 (96.88%)
High frequency (n = 135)	101 (74.81%)	27 (20.00%)	7 (5.19%)	128 (94.81%)
χ^2				0.696
P				0.404

lar quality of life outcomes across all measured domains.

Comparison of adverse events between the low frequency group and high frequency group

No significant differences were observed in adverse events between the low- and high-frequency groups ($P > 0.05$) (**Table 7**). These findings indicate a similar safety profile for both frequencies regarding adverse events.

Comparison of patient satisfaction between the low frequency group and high frequency group

Patient satisfaction levels were high in both the low- and high-frequency groups (**Table 8**). The overall satisfaction rate was 96.88% for the low-frequency group and 94.81% for the high-frequency group, with no significant difference ($P > 0.05$). Both treatment groups demonstrated high overall patient satisfaction.

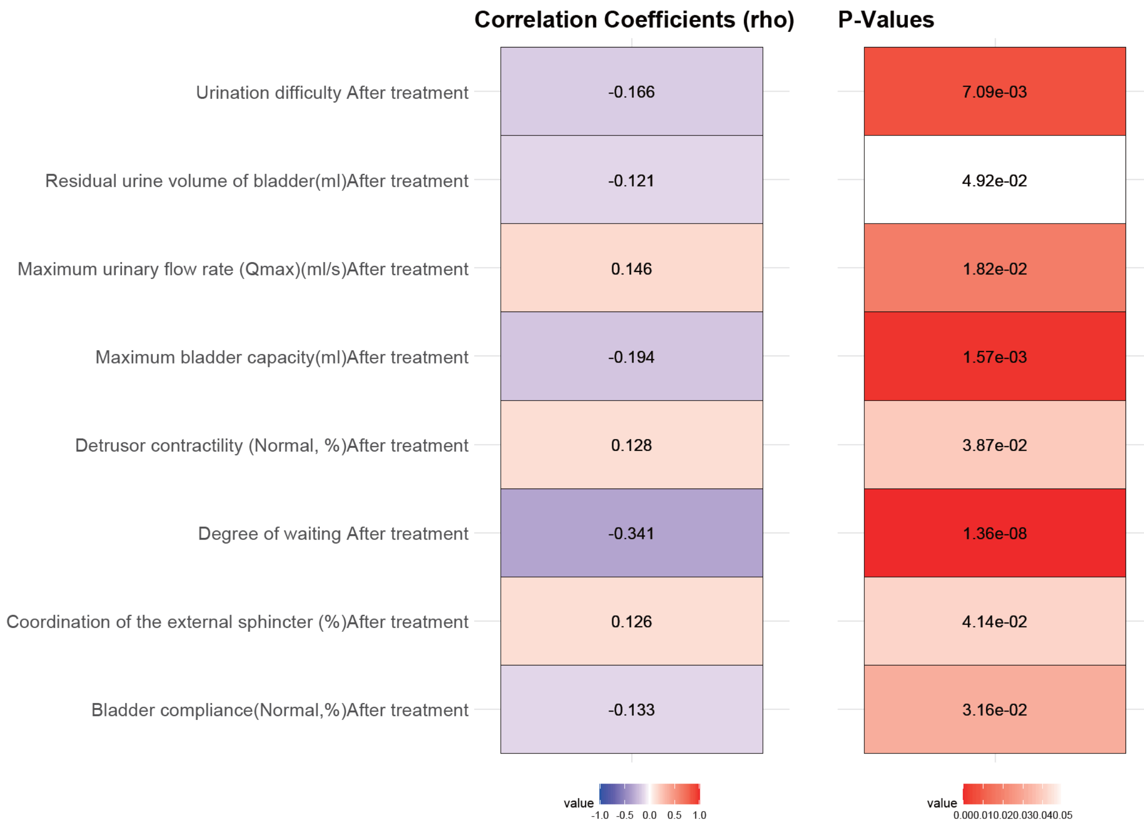

Figure 1. Correlation analysis between sacral nerve modulation frequency and urodynamic parameters.

Correlation analysis between SNM frequency and urodynamic parameters

The correlation analysis between SNM frequency and urodynamic parameters revealed several significant associations (**Figure 1**). A positive correlation was observed between modulation frequency and maximum urinary flow rate (Qmax) after treatment (rho = 0.146, P = 0.018), indicating improved flow with higher frequencies. Conversely, maximum bladder capacity negatively correlated with the frequency of modulation (rho = -0.194, P = 0.002), suggesting a reduction in capacity at higher frequencies. Residual urine volume also showed a negative correlation (rho = -0.121, P = 0.049), indicating less urine retention with increased frequency. Positive correlations were noted for detrusor contractility and coordination of the external sphincter after treatment (rho = 0.128, P = 0.039, and rho = 0.126, P = 0.041, respectively), suggesting improved function at higher frequencies. Bladder compliance exhibited a slight negative correlation with frequency (rho = -0.133, P = 0.032). Urination difficulty and degree of waiting were both negatively correlated with modulation frequency, with rho values of -0.166 (P = 0.007) and -0.341 (P < 0.001), respectively, indicating that higher frequencies were associated with reduced urination difficulty and shorter waiting times. These correlations highlight the intricate relationship between frequency modulation and various urodynamic outcomes.

Discussion

In this study, we investigated the characteristics of urodynamic parameters in patients undergoing sacral neuromodulation (SNM) therapy with different stimulation frequencies. Our findings provide nuanced insights into the differential impacts of low and high-frequency stimulation on bladder function, urination difficulty, and quality of life. While some outcomes were similar across both frequencies, our results reveal important differences in efficacy and patient response based on modulation frequency.

One of the most notable observations was the differential improvement in Qmax between the low and high-frequency groups. Post-treatment, patients in the high-frequency group exhibited a significantly superior Qmax compared to those in the low-frequency group. This indicates that higher frequencies may enhance the neuromodulatory effect on the detrusor-sphincter complex, leading to a more efficient voiding phase of micturition. Previous studies [20, 21] have suggested that high-frequency stimulation may increase neuronal firing rates and synaptic efficacy within the spinal cord and brainstem circuits responsible for micturition. This upregulation in synaptic connectivity may enhance the coordination between the urinary sphincter and detrusor muscle contraction, reducing outflow resistance during urination [22].

Contrastively, maximum bladder capacity increased more significantly in the low-frequency group compared to the high-frequency group post-treatment. This suggests that lower frequencies may exert a stabilizing effect on bladder storage function. Low-frequency stimulation might promote a more accommodative bladder by modulating afferent signaling pathways [23]. Such regulation could decrease bladder overactivity by downregulating hyperreflexia, a hallmark of conditions like overactive bladder syndrome [24]. This finding underscores that while high-frequency stimulation is effective in improving bladder emptying, low-frequency stimulation may be preferable in cases where bladder storage issues are more prominent. Thus, a dual approach could allow for more customized treatment plans, tailored to an individuals' urodynamic profiles.

Our study also demonstrates significant changes in detrusor contractility and the coordination of the external sphincter, especially in the high-frequency group. The heightened contractility likely results from enhanced recruitment of motor neurons and inhibition of inhibitory interneurons, which collectively enhance the contractile strength of the detrusor muscle during voiding [25, 26]. The improved coordination of the external sphincter suggests that high-frequency stimulation optimizes the timing and dynamics of sphincter relaxation during micturition, facilitating a more complete and uninterrupted bladder emptying process. This aligns with the current understanding of sacral neuromodulation's effects on neural circuits, which involve the reorganization and strengthening of neural pathways connecting the bladder and pelvic floor muscles [24, 27].

Residual urine volume, reflecting post-void efficiency, decreased more markedly in the high-frequency cohort, possibly due to better coordination and stronger detrusor contractions [28]. This reinforces the suitability of high-frequency modalities for reducing the risks of urinary tract infections or bladder stones, both of which can result from urine stagnation [29]. Conversely, abdominal pressure required to initiate urination did not significantly differ post-treatment, suggesting that modulation frequencies predominantly affect neural, rather than mechanical, aspects of the lower urinary tract's function.

Though bladder compliance improved in the low-frequency group, potentially through the stabilization of afferent signaling and the enhancement of the viscoelastic properties of the bladder wall, these changes highlight the need for frequency-specific strategies when addressing different urodynamic anomalies [30, 31]. The negative correlation between high-frequency modulation and bladder compliance underscores that while high-frequency stimulation acutely improves voiding dynamics, it may not provide similar benefits for bladder storage function.

A significant finding pertains to urination difficulty and waiting times, both of which showed substantial improvements across groups, with a more pronounced effect in those receiving high-frequency stimulation. These improvements are likely due to increased neural plasticity and enhanced coordination between the detrusor and external sphincter, which optimizes both conscious and reflexive urinary pathways. Specifically, the micturition reflex arc and its cortical modulation via sensory feedback, likely plays a key role in this improvement [32, 33].

Despite the varying impacts on urodynamic profiles, quality of life improvements were not significantly different across frequencies. The SF-36 scores suggest that while physiological improvements were frequency-dependent, the subjective perception of quality of life was similarly elevated in both groups. This suggests that the symptom relief experienced by patients, characterized by reductions in frequency and urgency, contributed to enhanced psychosocial functioning, irrespective of the specific frequency used.

The adverse event profile offers further supports the safety of both frequencies, with no significant differences between them. This highlights the robustness and procedural safety of SNM across different settings. The slightly higher incidence of urinary tract infections and hematuria in the high-frequency group may be attributed to heightened voiding pressures and more frequent procedural adjustments during optimization [34, 35]. However, these adverse events remain within acceptable safety parameters.

Patient satisfaction levels were generally robust across groups, likely reflecting the perceived relief from bladder dysfunction rather than specific urodynamic improvements. The marginally higher dissatisfaction in the high-frequency group, albeit statistically insignificant, might be attributed to non-responders or those experiencing more pronounced procedural discomfort or extended adjustment periods [36].

While this study provides valuable insights into the effects of different SNM therapy frequencies on urodynamic parameters, it is not without limitations. The observational study design restricts our ability to infer causality between stimulation frequency and urodynamic outcomes. Additionally, the sample size, though sufficient to identify significant trends, may not capture the full breadth of individual variations in response to neuromodulation. The study period was also relatively short, raising questions about the long-term efficacy and safety of the different frequencies. Furthermore, reliance on subjective measures of patient satisfaction and quality of life, without incorporating validated questionnaires, may introduce bias. Future research should consider randomized controlled trials and incorporate long-term follow-up to corroborate these findings and address these limitations more comprehensively.

Conclusion

Overall, this study underscores the importance of individually tailored sacral neuromodulation therapies. The interplay between neural adaptation and physiological response to different frequencies emphasizes the need to consider a patient's baseline urodynamic parameters and therapeutic goals, whether that be increasing bladder capacity, optimizing bladder emptying, or reducing urinary frequency, when choosing the appropriate SNM frequency. Future research should focus on elucidating the long-term sustainability of these effects and exploring the molecular and neuroplastic changes that underpin these clinical outcomes. Such insights will be crucial in refining neuromodulation strategies, not only for bladder dysfunction but potentially for other areas of neuro-urology and functional neural rehabilitation.

Disclosure of conflict of interest

None.

Address correspondence to: Yuansong Xiao, Department of Urology, PLA General Hospital of Southern Theater Command, No. 111 Liuhua Road, Guangzhou 510010, Guangdong, China. E-mail: yuansongdoctor@163.com

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