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ORIGINAL ARTICLE

Variation in bony landmarks and predictors of success with sacral neuromodulation

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Abstract

Introduction and hypothesis We assessed variations in sacral anatomy and lead placement as predictors of sacral neuromodulation (SNM) success. Based solely on bony landmarks, we also assessed the accuracy of the 9 and 2 protocol for locating S3.

Methods This is a retrospective cohort study performed from October 2008 to December 2016 at the University of North Carolina at Chapel Hill. Fluoroscopic images were used to assess sacral anatomy and lead location. Success was defined as >50% symptom improvement after stage I and clinical response at most recent follow-up.

Results Of 249 procedures, 209 were primary implants and 40 were revisions among 187 (89.5%) women and 22 (10.5%) men. Success rate was 83.3% for primary implants and 89.4% for revisions. Success was associated with shorter implant duration (21.3 ± 22.2 vs 33.6 ± 25.8 months), higher body mass index (30.3 ± 7.8 vs 27.6 ± 6.1 kg/m^2), and straight vs curved lead (90.5% vs 80.5%) (all $p = .05$), but not with sacral anatomy or lead placement. In assessing the 9 and 2 protocol, mean distance from coccyx to S3 did not equal 9 cm: 7.4 ± 1.0 vs 7.2 ± 0.8 cm ($p = .26$), while mean distance from midline to S3 did equal 2 cm: 1.9 ± 0.4 vs 2.0 ± 0.7 cm ($p = .37$).

Conclusions Variations in sacral anatomy and lead placement did not predict SNM success. The 2-cm protocol was verified while the 9-cm protocol was not, although neither was predictive of success, which may obviate the need to mark bony landmarks prior to fluoroscopy.

Keywords Bony landmarks · Fluoroscopy · Lead wire · Sacral S3 foramen · Sacral anatomy · Sacral neuromodulation

Introduction

Sacral neuromodulation (SNM) is a recognized therapy for refractory overactive bladder (OAB), nonobstructive chronic urinary retention, and fecal incontinence (FI) [1]. Optimal placement of the tined lead strives to stimulate sacral nerve S3 due to its innervation of the pelvic organs, without impacting lower-extremity function [2]. Location of the S3 sacral foramen is crucial for successful lead placement. Previous identification of the S3 foramen focused on palpation of the greater sciatic notch; however, this is not easily palpable in all individuals [1]. Thus, other techniques have been proposed that rely on palpable bony landmarks, such as the midline spinous processes, tip of the coccyx, and sacroiliac joints [1]. The most widely recognized method for locating the S3 foramen recommends measuring 9 cm cephalad from the tip of the coccyx and 2 cm lateral from midline, based on a cadaveric study [3]. We refer to this technique as the 9 and 2 protocol. While use of bony landmarks for placement of the tined lead was largely developed for office percutaneous nerve evaluation (PNE), many still advocate starting the operative procedure in similar fashion by placing surface markings based on bony landmarks [4], with some suggestion that this might minimize use of fluoroscopy [2]. Use of bony landmarks in staged tined-lead placement, however, results in interobserver variability and still requires the use of intraoperative fluoroscopy for confirmation of the S3 foramen [5], often

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with multiple lead adjustments during the procedure [6]. Further, not all individuals are appropriate for PNE, and studies have demonstrated that operative staged procedures have higher progression to pulse-generator implantation [7], thus, techniques for operative SNM remain important.

There is limited evidence assessing individual variation in sacral anatomy and lead placement and whether these factors affect the clinical success of SNM. Prior studies examining the relationship between bony landmarks and S3 foramen location include magnetic resonance imaging (MRI) [8], computed tomography (CT) [9, 10], and cadavers [2, 3, 11, 12], but not fluoroscopy, although this represents the standard imaging modality used for intraoperative assessment of lead placement. Prior studies are limited by small sample size and no association with clinical success. Therefore, we chose to use intraoperative fluoroscopy images to assess variation in bony anatomy, as well as the association between sacral anatomic landmarks, lead location, and clinical success. Our primary objective was to assess variations in sacral bony anatomy and lead placement as predictors of SNM success. Our secondary objective was to assess the accuracy of the 9 and 2 protocol as the recommended measurements using bony landmarks to identify the S3 foramen.

Materials and methods

Institutional Review Board approval was obtained through the University of North Carolina at Chapel Hill (UNC). This was a retrospective cohort study of women and men aged ≥18 years who underwent SNM from October 2008 to December 2016 at UNC facilities. Participants were drawn from the UNC Division of Female Pelvic Medicine and Reconstructive Surgery, Department of Urology, and Division of Colorectal Surgery. Participants were assigned to one of two cohorts based on SNM response: success vs failure. Success was defined as >50% symptom improvement after implant and documented clinical response at the most recent follow-up visit. Images were excluded if fluoroscopic quality was suboptimal for obtaining measurements. One participant was excluded due to bilateral lead placement during the same surgical procedure, preventing evaluation of the separate effects of each lead.

Intraoperative fluoroscopic images, including both posterior–anterior (PA) and lateral views, were collected from the electronic medical record (EMR) to assess sacral anatomy and lead location. As with all fluoroscopic images obtained intraoperatively, there was noted variation in field of view (FOV) and level of zoom magnification at the time of image capture, without a scale embedded into the images. While we used the image capture software to perform our measurements, we had to create a reference for measurement, and therefore the implanted lead was used as this reference measure due to its uniform length. The electrode portion of the lead was measured on a sample lead, from the inferior edge of the most distal electrode (electrode 0) to the superior edge of the most proximal (electrode 3). Using this method, the electrode portion for the straight lead measures 2.1 cm and for the curved lead 2.4 cm, with the curved lead being longer due to a longer electrode 1. The difference in the visual appearance of electrode 1 allowed us to distinguish between lead types on fluoroscopy. This terminology for lead type (straight vs curved) reflects the nomenclature defined by the manufacturing company and is referred to in this manner for the remainder of this discussion. With this standard reference measurement, we were able to measure the length from electrode 0 to electrode 3 on the lead for each fluoroscopic image and use this as a reference for all other 2D measurements performed. Separate reference measurements were taken for each lateral and PA image. With intraoperative fluoroscopy, it is standard practice to adjust the C-arm relative to the patient to obtain accurate lateral and PA images without distortion. Confirmation of accurate imaging is achieved through visual inspection of the real-time images during the implantation procedure. Given this practice of intraoperative assessment of image quality, we would not expect image quality or accuracy to interfere with use of the lead for reference measurement. We further evaluated the reproducibility of using the lead wire as a reference measure by assessing two sets of bony landmark measurements on a subset of individuals with both primary implants and revisions. For our primary outcome, we assessed sacral bony anatomy and lead placement as predictors of SNM success. Bony anatomic landmarks measured on lateral fluoroscopic images included distance from tip of coccyx to S3 along the dorsal sacral surface, distance from tip of coccyx to S3 along the ventral sacral surface, distance from tip of coccyx to the sacral promontory, and sacral width at S3. Dorsal and ventral surface measurements from tip of coccyx to S3 were terminated at the cephalad aspect of S3, corresponding to the technique used by Deveneau et al. in the cadaveric study, on which bony landmark parameter measurements in SNM are based [3]. For measurements along the sacral surfaces, we assessed both straight and curved line measurements; although curved line measurements are not depicted in the figures to avoid obscuring other measurements (Figs. 1 and 2). Bony anatomic landmarks measured on PA fluoroscopic images included the distance from midline spine to S3 (Fig. 3).

Lead placement characteristics assessed on lateral images included lead type (curved vs straight) and location (S2, S3, or S4 foramen), depth of electrode 3 relative to the dorsal and ventral surfaces of the sacrum at S3, lead orientation (directed caudad, straight, or cephalad), and angle of insertion at S3 (Fig. 2). Lead placement characteristics evaluated on PA fluoroscopic images included depth of electrode 3 relative to the S3 foramen (Fig. 3). For the depth of electrode 3 relative to the

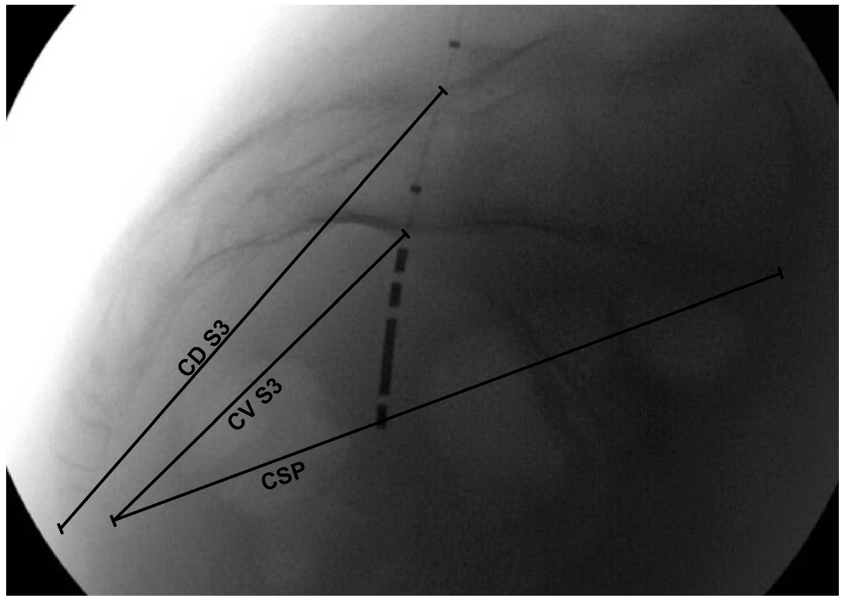

Fig. 1 Lateral images of sacral bony anatomy. *CD S3* Distance from tip of coccyx to dorsal surface of S3 foramen (9 cm protocol). *CV S3* Distance from tip of coccyx to ventral surface of S3 foramen. *CSP* Distance from tip of coccyx to sacral promontory

ventral sacral surface, if it was at the ventral sacrum, its value was zero; if it was superior to the ventral sacrum, it was positive; if it was inferior, it was negative.

For our secondary outcome, we assessed 9 and 2 protocol accuracy as the recommended measurements using bony landmarks to identify the S3 foramen, based on measuring 9 cm cephalad from the tip of the coccyx and 2 cm lateral from midline. Lateral images were used to measure the distance from tip of coccyx to dorsal aspect of S3 to evaluate the 9-cm portion of the protocol; both straight- and curved-line measurements were assessed. PA images were used to measure the distance from midline spine to S3 to evaluate the 2-cm portion of the protocol. We then compared means for these measurements in our study population to the recommended 9 cm and 2 cm, respectively.

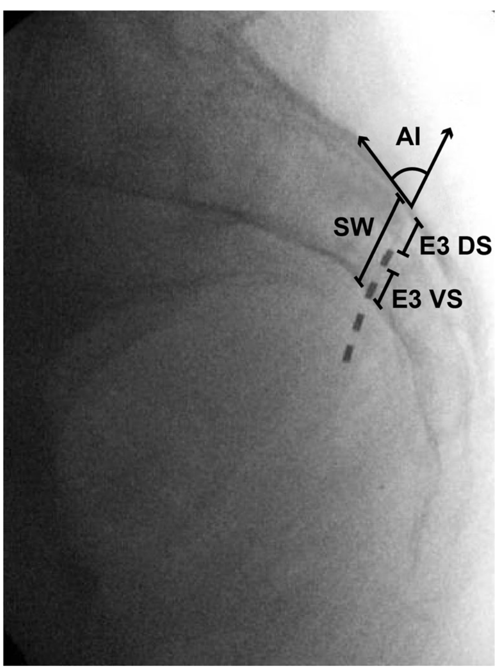

Fig. 2 Lateral Images of lead-wire placement. *AI* Angle of insertion of lead wire into sacrum. *SW* Sacral width at S3 foramen. *E3 DS* Distance from electrode 3 to dorsal sacrum. *E3 VS* Distance from electrode 3 to ventral sacrum

Demographics were abstracted from the EMR, including age, gender, race, height, weight, body mass index (BMI), indication(s) for SNM (e.g., refractory OAB, nonobstructive urinary retention, and/or FI), type of implant (staged vs full implant after office PNE), operative time, surgeon, and chronic medical and neurologic conditions (including bony abnormalities and history of spinal surgery). We also assessed current SNM status (intact, revised, or removed), duration of implant, indication for removal or revision, and evidence of clinical success or failure at most recent follow-up.

Data were analyzed using SPSS 24 (IBM, Armonk, NY, USA). Bivariate analyses were performed with Student's *t* test for independent continuous variables and Pearson's chi-square and Fisher's exact tests for independent categorical variables. Although there were many variables analyzed overall, our analysis was structured such that variables were categorized and assessed in smaller subsets, thereby minimizing family-wise error.

Results

There were 249 lead insertions, of which 209 were primary implants and 40 were revisions (34 first revisions, 6 second revisions). Mean follow-up was 22.7 ± 22.9 months. There were 187 (89.5%) women and 22 (10.5%) men. Indications for SNM included refractory OAB (54.1%), nonobstructive urinary retention (14.4%), and FI (31.6%), with 12.4% having a dual indication. Success rate was 83.3% for primary implants

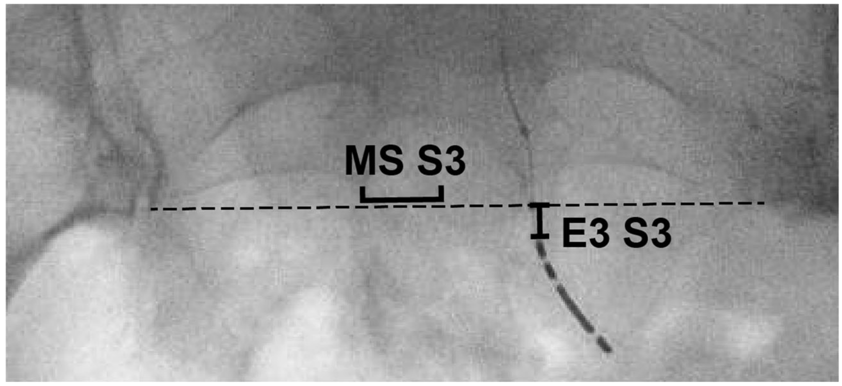

Fig. 3 Posterior–anterior (PA) images of sacral bony anatomy and lead-wire placement. *MS S3* Distance from midline spine to medial aspect of S3 foramen (2 cm protocol). *E3 S3* Distance from electrode 3 to S3 foramen. This is based on SI joint landmark (imaginary line drawn across bilateral SI joints used clinically to estimate location of S3 foramen on PA view)

and 89.4% for revisions based on >50% clinical response maintained at most recent follow-up visit. Revisions performed for indications other than clinical failure were not designated as failures. Comparing those with successful vs failed implant, success was associated with a higher BMI and shorter implant duration (Table 1). There were no differences in success based on gender, race, age at implant, indication for SNM, staged vs full implant, or other demographics.

When assessing variation in bony sacral anatomy and lead placement, our study population had minimal individual variation, as demonstrated by relatively narrow standard deviations for all sacral bony anatomy and lead measurements. For our primary outcome, we evaluated sacral bony anatomy and lead location as predictors of SNM success. Success was not associated with measurements of sacral bony anatomy (Table 2). We also assessed operative time as a proxy for difficult lead placement, but bony anatomy did not correlate with operative time (Table 1). With respect to lead placement, success was associated with the straight vs curved lead, but not lead location, orientation, angle, or depth of electrode 3 (Table 3).

For our secondary outcome, we assessed accuracy of the 9 and 2 protocol as the recommended measurements using bony landmarks to identify the S3 foramen. For the 9-cm protocol, the recommendation is to measure 9 cm cephalad from the tip of the coccyx to locate S3. However, in our population, mean distance was 7.3 ± 1.0 cm (straight line) and 7.8 ± 1.1 cm (curved line). (Table 2). For the 2-cm protocol, the recommendation is to measure 2 cm lateral from the midline spine at S3. In our population the mean distance from the midline to S3 was 1.9 ± 0.4 cm. We also assessed the 9 and 2 protocol by gender. Mean distance for the 9-cm protocol for women was 7.3 ± 1.0 cm (straight line) and 7.7 ± 1.1 cm (curved line) and for men 7.6 ± 0.9 cm (straight line) and 8.0 ± 1.0 cm (curved line). Mean distance for the 2-cm protocol for women was 1.9 ± 0.4 cm and for men 2.0 ± 0.4 cm.

To confirm fluoroscopic image quality and accuracy and reproducibility of using the lead wire as a reference measure, we compared intraoperative images on a subset of individuals who had both primary implant and revisions. Measurements were compared between primary and revision fluoroscopic images, with evaluation of the 9 and 2 protocol (tip of the coccyx to dorsal S3 and midline to medial S3). Comparisons showed minimal deviation between primary and revision measurements: tip of the coccyx to dorsal S3 had a mean percentage difference of 1.7 ± 1.7% and midline to medial S3 a mean difference of 1.9 ± 1.2%.

For some participants, not all measurements could be completed due to suboptimal imaging quality, including absent PA imaging (0.9%), inability to visualize the entire coccyx (16.3%), and saved images did not represent final lead placement (0.5%). All participants had available fluoroscopic images that permitted assessment of the majority of sacral bony anatomy and lead-placement measurements.

Discussion

SNM success rates in our population were high and unassociated with individual variation in sacral bony anatomy or lead-placement parameters. Overall, we sought to assess and characterize variation in sacral anatomic parameters. Our study population had a small degree of individual variation, as demonstrated by fairly narrow standard deviations for all sacral bony anatomy and lead measurements. Regarding the 9 and 2 protocol, mean distance from the tip of the coccyx to S3 was actually closer to 7 cm, while lateral distance from midline to S3 was similar at 2 cm, advocating for reconsideration of this measurement technique.

When comparing our findings with the published literature, Jairam et al. found that lead-placement parameters, such as orientation, location, angle of insertion, or relative depth of electrode 3, were not associated with success [13]. However, that study included only short-term success and did not assess sacral anatomy [13]. Interestingly, we found that the straight (vs curved) lead was associated with success. The curved lead and stylet were developed for SNM to better follow the course of sacral nerve S3, suggesting that closer proximity of the electrodes to the nerve could lead to improved outcomes [4, 14]. In testing the curved vs straight lead, Jacobs et al. revealed that the curved lead achieves motor response at lower

Table 1 Demographic characteristics

	Success $N = 174$	Failure $N = 35$	P value
Age at implant (years)	62.0 ± 15.1	58.4 ± 15.6	0.20*
Gender			
Female	155 (89.1)	32 (91.4)	0.99***
Male	19 (10.9)	3 (8.6)	
Race			
Caucasian	150 (86.2)	27 (77.1)	0.30***
African American	16 (9.2)	7 (20.0)	
Hispanic	1 (0.6)	0 (0)	
Asian	2 (1.1)	1 (2.9)	
Other	3 (1.7)	0 (0)	
Mean BMI (kg/m^2)	30.3 ± 7.8	27.6 ± 6.1	0.05*
Tobacco use			
No	124 (71.3)	21 (60.0)	0.44**
Yes, prior	33 (19.0)	9 (25.7)	
Yes, current	17 (9.8)	5 (14.3)	
Chronic medical condition[a]	132 (75.9)	24 (68.6)	0.40**
Chronic neurologic condition[b]	25 (14.4)	7 (20.0)	0.44**
Spinal bony abnormality	109 (62.6)	25 (71.4)	0.34**
Rheumatoid arthritis	6 (3.4)	0 (0)	0.59***
Osteoarthritis	56 (32.2)	17 (48.6)	0.08**
History of spinal surgery	34 (19.5)	8 (22.9)	0.82**
Staged procedure	50 (28.7)	12 (34.3)	0.69**
Primary indication			
OAB	95 (54.6)	18 (51.4)	0.28**
Urinary retention	22 (12.6)	8 (22.9)	
FI	57 (32.8)	9 (25.7)	
Dual indication			
OAB plus retention	13 (7.5)	6 (17.1)	0.99***
OAB plus FI	4 (2.3)	3 (8.6)	0.09***
Time since implant (months)	21.3 ± 22.2	33.6 ± 25.8	0.05*
Operative time (min)	51.2 ± 20.0	50.6 ± 15.5	0.86*

Data presented as mean ± standard deviation or *n* (%)

BMI body mass index, *OAB* overactive bladder, *FI* fecal incontinence

[a] Hypertension, coronary artery disease, congestive heart failure, chronic kidney disease, chronic obstructive pulmonary disease, chronic liver disease, inflammatory bowel disease, prior gastric bypass, sickle cell disease, diabetes mellitus, sarcoidosis, systemic lupus erythematosus, thyroid disorder, human immunodeficiency virus, acquired immunodeficiency syndrome

[b] Multiple sclerosis, Parkinson's disease, Huntington's disease, prior stroke/transient ischemic attack/traumatic brain injury with deficits, structural disease (e.g., brain/spinal tumor), other neuromuscular/motor neuron disease

*Student's *t*, **chi-square, ***Fisher's exact

amplitudes, which could impact battery longevity; however, a difference in overall success was not assessed [14]. Our results indicate that use of a curved lead does not appear to confer benefit with respect to success.

Table 2 Sacral bony anatomic measurements

	Success $N = 174$	Failure $N = 35$	P value
Dorsal coccyx to S3[a]			
Straight	7.4 ± 1.0	7.2 ± 0.8	0.26
Curved	7.9 ± 1.2	7.5 ± 0.9	0.10
Ventral coccyx to S3[a]			
Straight	6.2 ± 0.9	5.9 ± 0.8	0.09
Curved	6.6 ± 1.0	6.3 ± 0.8	0.11
Ventral coccyx to sacral promontory[a]			
Straight	11.1 ± 1.9	10.9 ± 1.3	0.58
Curved	13.4 ± 2.0	13.3 ± 1.4	0.80
Thickness of sacrum at S3[a]	1.9 ± 0.3	1.9 ± 0.2	0.41
Midline to medial S3[b]	1.9 ± 0.4	2.0 ± 0.7	0.37

Measurements in centimeters; data analyzed using Student's *t* test and presented as mean ± standard deviation

[a] Lateral image

[b] Posterior–anterior image

Table 3 Lead-placement parameters

	Success $N = 208$	Failure $N = 40$	P value
Lead type			
Straight	76 (36.5)	8 (20.0)	0.05*
Curved	132 (63.5)	32 (80.0)	
Lead location[a]			
S3	197 (94.7)	37 (92.5)	0.37**
S4	7 (3.4)	3 (7.5)	
S2	4 (1.9)	0 (0)	
Lead orientation[b]			
Caudad	68 (32.7)	13 (32.5)	0.97***
Straight	105 (50.5)	20 (50.0)	
Cephalad	32 (15.4)	7 (17.5)	
Lead angle (°)[a]	69.9 ± 11.1	69.4 ± 11.5	0.67***
Distance from electrode 3 to S3[b]			
Dorsal S3	1.3 ± 0.5	1.3 ± 0.6	0.48***
Ventral S3	0.3 ± 0.4	0.3 ± 0.4	0.68***
Depth of electrode to S3[b]	−0.5 ± 0.9	−0.6 ± 1.6	0.53***
Most superficial electrode inferior to sacrum[a]			
0	68 (32.7)	10 (25.0)	0.70**
1	105 (50.5)	23 (57.5)	
2	30 (14.4)	7 (17.5)	
3	2 (1.0)	0 (0)	

All measurements in centimeters unless otherwise specified; data presented as mean ± standard deviation or *n* (%)

[a] Lateral image

[b] Posterior–anterior Image

*Chi-square, **Fisher's exact, ***Student's *t* test

There is significant variation in the literature, with inconsistent association demonstrated between SNM success and demographic factors. The only demographic factor associated with success was higher BMI. Some studies have shown a correlation between success and lower BMI [15, 16], while others have shown no association [17, 18]. Although our findings therefore differ from those previously reported in the literature, it is difficult to draw a significant conclusion about the association between BMI and success, particularly as we found no association between success and height or weight. Female gender has been reported in association with higher success [13, 18–21]; however, other studies have shown no association [17] or included only female participants [15, 16]. Similar to our study, in the mixed-gender studies, there were low numbers of male participants, which may limit interpretation of this potential association. Association of success with age is also inconsistent, with certain studies reporting decreased success with higher age [13, 15, 16, 21] and others showing no association [17–20, 22]. While Richter et al. reported that medical comorbidities may be associated with decreased success [15], our findings were similar to Faris et al. [18] in that we found no association between medical or surgical history and SNM success. Finally, it is unclear whether placement indication impacts outcome, as some have shown an association between success and diagnosis of refractory OAB [20, 21], while others have found no difference based on diagnosis [13], which was our finding.

Due to the retrospective nature of our study—and most published in the literature—we may have been underpowered to detect a difference in outcomes. We thus performed a post hoc power analysis and found we had 61.7% power to detect a difference in our primary outcome of bony sacral anatomy as a measure of success. We specifically compared the distance from tip of the coccyx to S3 for the success vs failure groups for this post hoc analysis, given that our findings with respect to this measurement differ from prior studies. Ultimately, as success was not found to be associated with any of our primary measures (sacral bony anatomy and lead-placement parameters), logistic regression analysis was not performed, as this was felt to be of limited utility in this setting.

With respect to the 9 and 2 protocol, our results indicate that the mean distance from tip of coccyx to dorsal S3 in a population of men and women is on average closer to 7 cm, while the distance from midline to S3 was similar to the protocol at 2 cm. We found no differences in the 9 and 2 protocol by gender. These findings differ from the prior cadaveric study [3] that validated the 9 cm and 2 cm components for locating the S3 foramen. As part of that study, a needle was placed perpendicular to the sacrum at 9 cm cephalad to the coccyx and 2 cm lateral to the midline and kept in place during dissection. Deveneau et al. then assessed the distance from the tip of the coccyx to the superior aspect of S3, as well as the vertical distance from the needle tip to the superior aspect of S3. While the mean distance between the tip of the coccyx and S3 was 9 cm, there was substantial variation in this distance and in location of the needle tip relative to S3. The cadaveric study was also limited by small sample size (22 cadavers; 11 male and 11 female) [3].

A strength of our study is the use of a comprehensive, composite definition of success including >50% clinical improvement at time of implant and continued clinical response at most recent follow-up visit, with a mean follow-up of ~23 months. Most prior studies only examined short-term outcomes, with success defined by >50% symptom improvement to allow progress to stage II implant [13, 16–21]. Interpreting our findings in the context of prior studies suggests that while certain factors may be predictive of short-term success with a staged implant, these may not persist as predictors of long-term success. Richter et al. [15] and Amundsen et al. [23] did assess longer-term clinical response at 6 months and 2 years, respectively; however, they were limited to women with refractory OAB. Similarly, Hull et al. [24] and Altomare et al. [25] demonstrated long-term durability of SNM, both with minimum follow-up of 5 years but limited to use for FI. Unlike other studies that assessed either only FI or urinary indications, we evaluated participants undergoing SNM for all three approved indications for placement, which may contribute to the differences observed. Another strength is the large study population, which included both male and female participants from three distinct practice populations. We used fluoroscopy for measurements, which is not only unique but lends generalizability to the findings, given that this is the imaging modality used intraoperatively. We confirmed image accuracy and the reproducibility of using the lead wire as a reference measurement by comparing primary and revision images on individuals who had both sets of images. We also assessed both straight- and curved-line measurements, where applicable, which helps inform measurement practices and enhances generalizability of these findings.

Limitations of this study include its retrospective design. However, all data were objective and gathered from intraoperative fluoroscopy, decreasing the risk of recall, misclassification, and selection bias. Overall fluoroscopic image quality was good, with few instances of suboptimal images. While fluoroscopic imaging did not permit evaluation of skin-surface measurements, the cadaveric study by Deveneau et al. [3] provides precedent for the validity of using sacral surface measurements alone to characterize the sacral anatomy. This data does, however, draw from cadaveric dissection [3] and, therefore, the full degree to which adipose tissue and skin characteristics may impact sacral bony measurements in live individuals is not known. We used operative time as a proxy for difficult placement that could be related to excess adipose tissue or significant distortion of sacral anatomy and found no association with success. While we included participants of both genders, we lacked racial diversity due to our patient population, which is similar to prior studies. Race was not reported in prior cadaveric studies. Although our study included a single academic center, which may be different from a community-based center, our variety of practice types helps improve generalizability.

Success of SNM in our study population for all three approved indications was high, while individual variations in sacral bony anatomy and lead placement were minimal and not predictive of success. The recommended 9 and 2 protocol was not supported by our findings, and these measurements did not predict success. Use of fluoroscopy for intraoperative confirmation of the S3 foramen and lead-placement parameters is standard practice in operative SNM procedures. Our findings support the continued use of fluoroscopy for this purpose and suggest there may be limited utility in performing measurements based on bony landmarks initially, instead of proceeding directly with fluoroscopy. Future studies are needed to assess to what degree adipose tissue and skin characteristics may impact bony measurements. Clinicians may use these findings to be reassured that variation in patient bony anatomy and lead placement do not ultimately affect clinical success with SNM, with demonstration of satisfactory success rates.

Compliance with ethical standards

Conflicts of interest None.

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References

1. Chai TC, Mamo GJ. Modified techniques of S3 foramen localization and lead implantation in S3 neuromodulation. Urology. 2001;58(5):786–90.
2. Buchs NC, Dembe JC, Robert-Yap J, Roche B, Fasel J. Optimizing electrode implantation in sacral nerve stimulation–an anatomical cadaver study controlled by a laparoscopic camera. Int J Color Dis. 2008;23(1):85–91.
3. Deveneau NE, Greenstein M, Mahalingashetty A, Herring NR, Lipetskaia L, Azadi A, et al. Surface and boney landmarks for sacral neuromodulation: a cadaveric study. Int Urogynecol J. 2015;26(2):263–8.
4. Matzel KE, Chartier-Kastler E, Knowles CH, Lehur PA, Munoz-Duyos A, Ratto C, et al. Sacral neuromodulation: standardized electrode placement technique. Neuromodulation. 2017;20(8):816–24.
5. O'Haire C, Gibbons P. Inter-examiner and intra-examiner agreement for assessing sacroiliac anatomical landmarks using palpation and observation: pilot study. Man Ther. 2000;5(1):13–20.
6. Williams ER, Siegel SW. Procedural techniques in sacral nerve modulation. Int Urogynecol J. 2010;21(Suppl 2):S453–60.
7. Sutherland SE, Lavers A, Carlson A, Holtz C, Kesha J, Siegel SW. Sacral nerve stimulation for voiding dysfunction: one institution's 11-year experience. Neurourol Urodyn. 2007;26(1):19–28 discussion 36.
8. Saint Clair N, Boyles SH, Clark A, Edwards SR, Denman MA, Gregory WT. The presacral space and its impact on sacral neuromodulator implantation. J Urol. 2008;180(3):988–91.
9. McCullough MC, Decker S, Ford J, Downes K, Hilbelink D, Ordorica R, et al. Third sacral foramina morphometry for sacral neuromodulation. Female Pelvic Med Reconstr Surg. 2013;19(1):23–30.
10. Chung CP, Neese PA, Le HK, Bird ET. Computed tomography-guided S3 lead placement for sacral neuromodulation. Int Urogynecol J. 2013;24(2):349–51.
11. Hasan ST, Shanahan DA, Pridie AK, Neal DE. Surface localization of sacral foramina for neuromodulation of bladder function. An anatomical study. Eur Urol. 1996;29(1):90–8.
12. Povo A, Arantes M, Matzel KE, Barbosa J, Ferreira MA, Pais D, et al. Surface anatomical landmarks for the location of posterior sacral foramina in sacral nerve stimulation. Tech Coloproctol. 2016;20(12):859–64.
13. Jairam R, Marcelissen T, van Koeveringe G, van Kerrebroeck P. Optimal Lead positioning in sacral neuromodulation: which factors are related to treatment outcome? Neuromodulation. 2017;20(8):830–5.
14. Jacobs SA, Lane FL, Osann KE, Noblett KL. Randomized prospective crossover study of interstim lead wire placement with curved versus straight stylet. Neurourol Urodyn. 2014;33(5):488–92.
15. Richter HE, Amundsen CL, Erickson SW, Jelovsek JE, Komesu Y, Chermansky C, et al. Characteristics associated with treatment response and satisfaction in women undergoing OnabotulinumtoxinA and sacral neuromodulation for refractory urgency urinary incontinence. J Urol. 2017;198(4):890–6.
16. Levin PJ, Wu JM, Siddiqui NY, Amundsen CL. Does obesity impact the success of an InterStim test phase for the treatment of refractory urge urinary incontinence in female patients? Female Pelvic Med Reconstr Surg. 2012;18(4):243–6.
17. Dudding TC, Pares D, Vaizey CJ, Kamm MA. Predictive factors for successful sacral nerve stimulation in the treatment of faecal incontinence: a 10-year cohort analysis. Color Dis. 2008;10(3):249–56.
18. Faris AER, Gill BC, Pizarro-Berdichevsky J, Dielubanza E, Clifton MM, Okafor H, et al. Impact of age and comorbidities on use of sacral neuromodulation. J Urol. 2017;198(1):161–6.
19. Cameron AP, Anger JT, Madison R, Saigal CS, Clemens JQ, Urologic diseases in America P. National trends in the usage and success of sacral nerve test stimulation. J Urol. 2011;185(3):970–5.
20. Anger JT, Cameron AP, Madison R, Saigal C, Clemens JQ, Urologic diseases in America P. Outcomes of sacral neuromodulation in a privately insured population. Neuromodulation. 2016;19(7):780–4.
21. Amundsen CL, Romero AA, Jamison MG, Webster GD. Sacral neuromodulation for intractable urge incontinence: are there factors associated with cure? Urology. 2005;66(4):746–50.
22. Komesu YM, Amundsen CL, Richter HE, Erickson SW, Ackenbom MF, Andy UU, et al. Refractory urgency urinary incontinence treatment in women: impact of age on outcomes and complications. Am J Obstet Gynecol. 2018;218(1):111.e1–9.
23. Amundsen CL, Komesu YM, Chermansky C, Gregory WT, Myers DL, Honeycutt EF, et al. Two-year outcomes of sacral neuromodulation versus OnabotulinumtoxinA for refractory urgency urinary incontinence: a randomized trial. Eur Urol. 2018.
24. Hull T, Giese C, Wexner SD, Mellgren A, Devroede G, Madoff RD, et al. Long-term durability of sacral nerve stimulation therapy for chronic fecal incontinence. Dis Colon Rectum. 2013;56(2):234–45.
25. Altomare DF, Giuratrabocchetta S, Knowles CH, Munoz Duyos A, Robert-Yap J, Matzel KE, et al. Long-term outcomes of sacral nerve stimulation for faecal incontinence. Br J Surg. 2015;102(4):407–15.