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ORIGINAL ARTICLE

Growth modulation and remodeling by means of posterior tethering technique for correction of early-onset scoliosis with thoracolumbar kyphosis

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Abstract
Purpose The aim of this study is to evaluate the role of the non-fusion instrumented procedure with compression adjunct to lengthening by distraction in facilitating spinal modulation of the wedged peak vertebra, in patients with congenital thoracolumbar kyphosis/kyphoscoliosis according to the Hueter–Volkmann law. The authors seek to address the progressive modulation of the most wedged vertebra by analyzing the subjects' pre-operative and latest follow-up sagittal radiograph.
Methods Ongoing data collection of 14 peak wedged vertebra modulation during surgical management of 13 patients with Type I congenital thoracolumbar kyphosis (5 patients) or kyphoscoliosis (8 patients). Age at initial surgery averaged 58.6 months, with mean follow-up of 55.6 months (24–78). All were done with hybrid rib construct with clawing fashion through a single posterior approach with at least 4 lengthenings.
Results Two vertebral bodies were selected, the peaked deformed vertebrae within the instrumentation compression level (WICL) and the vertebrae nearest but outside the instrumentation compression process (OICL). Anterior vertebral body height (AVBH) and posterior vertebral body height (PVBH) were measured in both vertebral bodies. Regarding measured vertebrae (WICL), average preoperative AVBH/PVBH ratio significantly increased from 0.54 to 0.77 in the final follow-up. Regarding measured vertebrae (OICL), the average preoperative AVBH/PVBH ratio increased from 0.76 to 0.79 in the final follow-up. Modulation can be confirmed in the most deformed vertebrae (WICL) as the difference between the change in AVBH/PVBH ratio between vertebrae (OICL) and (WICL) was statistically significant ($P < 0.001$).
Conclusions Through the compression model adjunct to lengthening through distraction implemented in the surgical management of early-onset scoliosis, wedging improves through vertebral modulation (WICL) in comparison with the (OICL). This calls for further studies on the impact of surgical correction of EOS on modulation of the vertebrae.

Keywords Posterior tethering technique · Non-fusion technique · Early-onset scoliosis · Thoracolumbar kyphosis · Vertebral modulation

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Introduction

Congenital kyphosis is an uncommon spinal deformity, which arises from defective embryologic development of one or more vertebrae. The deformed vertebrae can be detected at birth or even prenatally, but the clinical presentation may be delayed till later in childhood [1]. Most deformities are at the thoracolumbar junction [2].

Even though kyphosis is less common than scoliosis, its consequences are more catastrophic if left neglected or insufficiently treated. Aside from the cosmetic impairment of the progressive curvature, the close relation of the vertebral column development with that of the spinal cord may pose significant threat on the spinal cord as the curve progresses [3].

Wedged vertebra due to incomplete failure of formation will culminate into asymmetrical growth of the vertebra [10] as the growth of the convex (posterior) part will

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surpass the growth of the concave (anterior) part. Eventually, the spinal curve due to a wedged vertebra will progress steadily if left untreated [13].

Non-surgical interventions are not effective in decreasing the progression of kyphotic deformities [4]. Surgical intervention in early life is thought to be a cornerstone for these patients, because this will prevent deterioration of neurologic deficits and reduce the need for surgeries in late life when the spine becomes stiffer [1, 5, 6]. The wedged vertebra is mostly trapped in the thoracolumbar junction, difficult to access, with complex pathologic anatomy, closely related to the spinal cord, and in an area with abundant vascularity. All of these factors make the surgical intervention very risky for neurological injury and inadequate correction of the curve [3].

In the past years, surgeons implemented classical surgical options for congenital kyphosis, which included posterior arthrodesis [7], combined anterior and posterior arthrodesis [1, 7]. Fusionless devices have been utilized to correct deformities of the spine [8–11].

In this study, posterior tethering technique with anchors above and below the peak wedged vertebrae associated with distraction-based growth-friendly implants with rib anchors was implemented as a surgical corrective procedure for congenital thoracolumbar kyphosis. The main objective of the study was to evaluate the role of the posterior tethering technique in facilitating vertebral modulation in congenital thoracolumbar kyphosis through Hueter–Volkmann principle. It is proposed that the wedging of the deformed vertebra decreases with time after utilizing the mentioned model.

Materials and methods

The study consisted of an institutional review board-approved retrospective review of the X-rays of 13 patients (8 males, 5 females) with congenital thoracolumbar kyphosis. All of the patients were noted to have a Type 1 deformity [7]. The patients underwent posterior tethering as an adjunct to distraction-based growth-friendly implants performed by the same surgeon, between September 2009 and November 2012. The patients had an average follow-up time of 55.6 months (24–78). The mean age at the time of the surgery was 58.6 months (24–120). Four patients had previous surgeries prior to the posterior tethering procedure; Table 1.

The operation was performed under general anesthesia, with the patient in the prone position. A straight longitudinal midline incision was performed from T2 downwards. Afterwards, the attached edge of the trapezius and rhomboidus major was dissected extraperiosteally and distracted laterally. Erector spinae muscles were also distracted laterally and exposed to the rib extraperiosteally. Two patients had three-rib construct beginning from the second rib and 11 patients had four-rib construct beginning from the second rib for 2 patients, from the third rib for 4 patients, from the fourth rib for 3 patients. The two proximal hooks were placed facing downwards and two distal ones facing upwards in the four-rib construct and one in the three-rib construct. Distally, screws were put (11 iliac, 2 lumbar).

Compression forces were applied through pedicular screws above and below the peaked deformed vertebra in 9 patients, and cross-links distally in 2 patients. An appropriately determined length, 4.5 titanium rod, was selected, contoured to maintain the adequate sagittal planes in the thoracic and lumbar regions locked with all the anchors. Two centimeters of the rod was preserved and locked distal to the distal anchors for future lengthening. C-arm and neuromonitoring were used in all cases. Mobilization was not restricted postoperatively.

Postoperative lengthening was performed every 6–9 months. The procedure included the following steps: the rods were lengthened by unlocking and distracting the distal screws distally (through the previously preserved 2 cm), which usually takes one or two lengthening times. Then, the rods were changed distally and the proximal rod was engaged with the distal one by domino for lengthening. Also, compression around the peaked deformed vertebra was applied through the anchors above and below it.

The patients had full-length spine radiographs in the coronal and the sagittal views standing or sitting preoperatively, postoperatively, and on follow-up sessions.

The radiographs underwent assessment of the deformed vertebrae, within instrumentation compression level (WICL) and the nearest one outside the instrumentation compression level (OICL) in all patients using Surgimap version 2.1.2 software. That included measuring the distance between the most anterior points on the superior and inferior endplates of the deformed vertebral body on the sagittal X-ray (represents the anterior vertebral body height (AVBH)), and the distance between the most posterior points on the superior and inferior endplates of the deformed vertebral body on the sagittal X-ray [represents the posterior vertebral body height (PVBH)] (Figs. 1, 2, 3). Afterwards, the ratio between the anterior and posterior vertebral body heights (AVBH/PVBH ratio) was calculated which was expected to reflect the extent of wedging in the selected vertebra [12–14]. Five patients had a final follow-up 3D CT scan which confirmed the reliability of the X-ray measurements of the vertebral body heights.

Measuring Cobb angles in coronal and sagittal views and T1–S1 spinal length was done.

Paired Student's *t* test and Wilcoxon rank test and independent *t* test were implemented via SPSS v20

Table 1 Preoperative clinical data for the patients in the study

Patient's number	Type of deformity	Peaked deformed vertebra	Age at surgery (months)	Follow-up period (months)
Patient #1	Syndromic	T12	36	57
Patient #2	Congenital	L1	36	59
Patient #3	Congenital	L2	48	60
Patient #4	Syndromic	L1	48	56
Patient #5	Congenital	L1	120	24
Patient #6	Syndromic	L1 and L2	72	31
Patient #7	Neuromuscular	L3	96	78
Patient #8	Syndromic	L1	60	48
Patient #9	Congenital	L1	48	59
Patient #10	Syndromic	T12	24	66
Patient #11	Syndromic	L1	36	69
Patient #12	Syndromic	T11	66	69
Patient #13	Neuromuscular	L1	72	47

software. For all tests, statistical significance was determined as a P value <0.05.

Results

All 13 patients (syndromic = 7, congenital = 4, neuromuscular = 2) underwent posterior tethering technique in adjunct to the lengthening procedures every 6–9 months. The mean follow-up time was 55.6 months (24–78). All underwent at least four lengthening procedures.

As for vertebral modulation, there were 14 peak deformed vertebrae (WICL) in the 13 patients (Table 2).

Preoperatively, the mean AVBH for the most deformed vertebrae (WICL) measured 6.58 mm, increased to 11.03 mm in the last follow-up visit ($P < 0.001$); the average increase in the AVBH was 75%. Yet, the PVBH of the most deformed vertebrae measured 12.01 mm preoperatively, increased to 14.22 mm in the last follow-up ($P = 0.001$). Average increase in the PVBH of 19.5% was observed. The average preoperative AVBH/PVBH ratio of the deformed vertebrae was 0.54 (0.35–0.69). In the last follow-up, the average ratio was 0.77 (0.68–0.9) which reflects the modulation in the wedging of the most deformed vertebrae. The difference in the AVBH/PVBH ratio was found to be statistically significant ($P < 0.001$).

For the vertebrae (OICL), the preoperative mean AVBH measured 9.96 mm, increased to 13.64 mm in the last follow-up ($P = 0.001$). The PVBH of these vertebrae measured 12.93 mm preoperatively, increased to 17.24 mm in the last follow-up ($P = 0.001$). The average increase in AVBH and PVBH was 40.15 and 35.05%, respectively. The average preoperative AVBH/PVBH ratio was 0.76 (0.48–0.88). In the last follow-up, the average ratio was 0.79 (0.53–0.89) ($P = 0.003$) (Table 3). The average increase in AVBH/PVBH ratio from preoperative settings to the last follow-up was only 2.39% in the vertebrae (OICL), compared with 23.5% for the most deformed vertebrae (WICL). Scoliosis and kyphosis Cobb angles were measured in all patients (Table 4).

Modulation is confirmed in the most deformed vertebrae (WICL) as the difference between the change in AVBH/PVBH ratio between vertebrae (OICL) and (WICL) was statistically significant ($P < 0.001$) (Table 5).

Six complications occurred: one had proximal hook dislodgment, one fracture in the 4th and 5th ribs, one infection surrounding a lumber screw, one distal rod penetrating the skin out, one wound infection after a lengthening procedure, and a patient had superior mesenteric artery syndrome which resolved after 2 days.

Discussion

Preserving spinal growth potential has been an intriguing idea in the treatment of early-onset scoliosis since the introduction of distraction instrumentation [15, 16]. Growth-sparing techniques were advantageous in correcting the abnormal spinal curvature while allowing the spinal growth to progress.

Posterior tethering technique through compression forces applied through anchors above and below the peaked deformed vertebra as an adjunct with distraction-based growth-friendly implants with rib anchors was developed as a surgical corrective modality for early-onset scoliosis associated with type 1 congenital kyphosis. Further correction and vertebral modulation was expected to occur through compression of the anchors above and below the

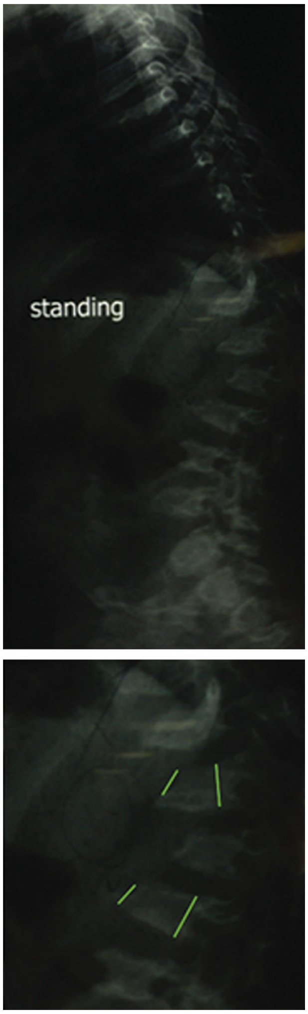

Fig. 1 A sagittal X-ray scan for a patient with thoracolumbar kyphosis before he underwent the surgery. The lines represent the anterior and posterior vertebral body heights preoperatively for L1 (6.8 and 10.32 mm), respectively, and for L3 (5.39 and 11.27 mm), respectively

peaked vertebrae. The AVBH, PVBH, and AVBH/PVBH ratio were measured in the vertebrae (WICL) in the sagittal X-rays. These measures were expected to address the modulation of the wedging of the peaked deformed vertebrae in comparison to the one (OICL).

The data in our study show that the preoperative mean AVBH and PVBH for the most deformed vertebrae (WICL) increased significantly in the most recent follow-up visit. However, the anterior segment growth rate is surpassing the posterior one. Also, the average preoperative AVBH/PVBH ratio of the deformed vertebrae increased in the latest follow-up, which reflects the significant modulation in the wedging of the deformed vertebrae (WICL).

Establishing spinal modulation through modifying the mechanical forces according to the Hueter–Volkmann principle was investigated in several animal models

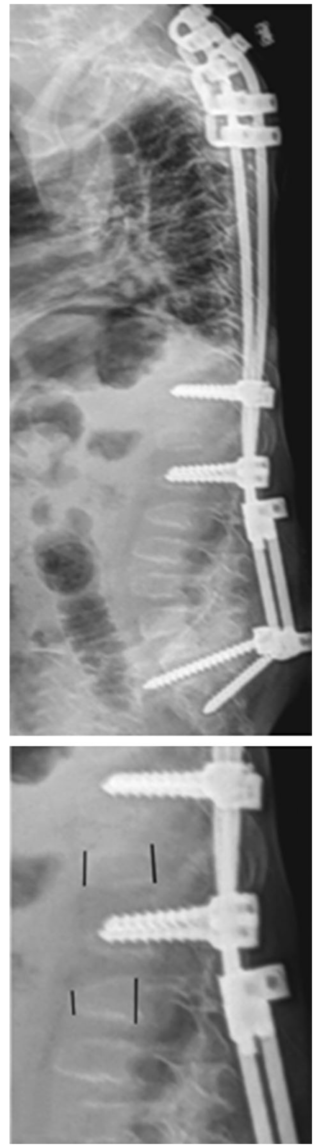

Fig. 2 A sagittal X-ray scan for the same patient in the last follow-up. It demonstrates the measurements for L1 (8.89 mm, and 10.08), respectively, and for L3 (6.26, 11.89), respectively, in the last follow-up. It is obvious that the distraction–compression model around the peaked deformed vertebra (L1) established more morphological changes and modulation in L1 than L3

[8, 17–21]. It was successful to induce an abnormal spinal curvature when the growth plates were put through asymmetrical compressive or tethering forces. Braun et al. demonstrated that using asymmetric tethering to induce vertebral wedging, absolute growth changes—in addition to relative or angular changes—on the concavity and convexity of the apical spinal segment can be predicted by the Hueter–Volkmann law. The findings of our study go along the concept of vertebral wedging modulation that Braun et al. concluded, but our absolute growth findings reflect significant remodeling in the vertebral wedging [24].

Fig. 3 A CT scan for the deformity in the last follow-up for the same patient with the anterior and posterior vertebral body heights for L1 (8.82 and 9.91 mm), respectively

Most of the animal model studies applied the vertebral modulation concept to scoliosis deformity. Though they are fundamentally different in geometry and loading from human spine [22], it may not be true to compare these findings with wedging modulation in the sagittal plane in thoracolumbar kyphosis deformities. Also, many of their outcomes were mostly illustrated as a change in the wedging angle, which is hard to compare with absolute growth values as in our study.

Recently, clinical trials for tethering in scoliosis with devices incorporating additional screws showed encouraging results [23]. But, we are unaware of any study in the literature that investigated the tethering technique with vertebral growth modulation with absolute growth values for kyphosis patients undergoing fusionless techniques.

Olgun et al. studied the growth stimulation for individual vertebrae in scoliosis patients with growing rods [24].

Table 2 The AVBH, PVBH and AVBH/PVBH ratio of the most deformed vertebrae (WICL) preoperatively and in the last follow-up

Patient number	Type of deformity	Level of deformity	Pre-op AVBH (mm)	Pre-op PVBH (mm)	Pre-op AVBH/PVBH ratio	Follow-up AVBH (mm)	Follow-up PVBH (mm)	Follow-up AVBH/PVBH ratio
Patient #1	Syndromic	T12	4.28	8.92	0.48	11.8	15.13	0.78
Patient #2	Congenital	L1	5.15	8.61	0.60	8.4	10.17	0.82
Patient #3	Congenital	L2	10.07	14.54	0.69	14.2	16.46	0.86
Patient #4	Syndromic	L1	10.32	14.88	0.69	12.8	15.37	0.83
Patient #5	Congenital	L1	7.15	15.46	0.46	7.55	16.57	0.46
Patient #6	Syndromic	L1	L1:6.35	12.96	0.48	11.04	14.85	0.74
		L2	L2:7.73	13.98	0.55	13.52	16.3	0.82
Patient #7	Neuromuscular	L3	8.8	17.05	0.51	15.7	18.98	0.83
Patient #8	Syndromic	L1	4.38	9.97	0.44	7.7	10.6	0.73
Patient #9	Congenital	L1	7.64	13.19	0.58	16.56	18.39	0.90
Patient #10	Syndromic	T12	3.55	9.98	0.35	8.24	11.84	0.69
Patient #11	Syndromic	L1	5.36	10.92	0.49	11.33	16.52	0.69
Patient #12	Syndromic	T11	4.55	7.44	0.61	6.7	7.85	0.85
Patient #13	Neuromuscular	L1	6.8	10.32	0.66	8.89	10.08	0.88
The mean			6.58	12.01	0.54	11.03	14.22	0.77

AVBH anterior vertebral body height, *PVBH* posterior vertebral body height, *AVBH/PVBH ratio* the ratio between anterior vertebral body height and posterior vertebral body height, and *(WICL)* within the Instrumentation Compression Level

Table 3 The AVBH, PVBH, AVBH/PVBH ratio preoperatively and in the last follow-up for the wedged vertebrae (OICL)

Patient number	Outside Vertebra nearest to implants	Pre-op AVBH	Pre-op PVBH	Pre-op ratio	Follow-up AVBH	Follow-up PVBH	Follow-up ratio
Patient #1	L2	5.39	9.15	0.59	13.11	20.11	0.65
Patient #2	L3	7.94	10.39	0.76	11.72	14.87	0.79
Patient #3	T11	9.72	13.3	0.73	13.95	17.96	0.78
Patient #4	L4	11.34	15.49	0.73	14.83	18.71	0.79
Patient #5	L4	9.95	14.97	0.66	12.25	18.91	0.65
Patient #6	L5	13.64	15.47	0.88	16.35	18.27	0.89
Patient #6	L5	13.64	15.47	0.88	16.35	18.27	0.89
Patient #7	L5	8.65	10.17	0.85	10.7	12.26	0.87
Patient #8	L3	11.39	14.37	0.79	12.37	15.85	0.78
Patient #9	L4	11.38	13.63	0.83	17.44	20.52	0.85
Patient #10	L3	11.85	14.22	0.83	19.3	22.78	0.85
Patient #11	L4	12.26	14.25	0.86	17.78	20.2	0.88
Patient #12	L4	6.84	8.87	0.77	8.52	10.7	0.8
Patient #13	L3	5.39	11.27	0.48	6.26	11.89	0.53
The mean		9.96	12.93	0.76	13.64	17.24	0.79

AVBH anterior vertebral body height, *PVBH* posterior vertebral body height, *AVBH/PVBH ratio* the ratio between anterior vertebral body height and posterior vertebral body height, and *(OICL)* outside the Instrumentation Compression Level

Table 4 Scoliosis and kyphosis levels for the patients with the Cobb angles in preoperative, postoperative, and last follow-up settings

Patient's number	Level of scoliosis deformity	Pre-op scoliosis Cobb angle	Post-op scoliosis Cobb angle	Follow-up scoliosis Cobb angle	Level of kyphosis deformity	Pre-op kyphosis Cobb angle	Post-op kyphosis Cobb angle	Follow-up kyphosis Cobb angle
Patient #1	T9–L1	53°	25°	29°	T10–L1	45°	25°	29°
Patient #2	T9–L3	100°	76°	89°	T10–L2	81°	29°	30°
Patient #3	L1–3	42°	30°	30°	L1–L3	27°	20°	8°
Patient #4	T11–L3	50°	16°	38°	T11–L3	40°	2°	11°
Patient #5	T8–L4	70°	60°	57°	T12–L2	58°	45°	41°
Patient #6	T11–L3	55°	26°	25°	T8–L2	55°	4°	11°
Patient #7	T11–L4	32°	26°	47°	L2–L5	75°	50°	62°
Patient #8	No curve	N/A	N/A	N/A	T11–L3	77°	27°	15°
Patient #9	T11–L2	20°	9°	10°	T10–L2	45°	3°	11°
Patient #10	No curve	N/A	N/A	N/A	T11–L1	63°	29°	7°
Patient #11	No curve	N/A	N/A	N/A	T11–L2	55°	26°	15°
Patient #12	No curve	N/A	N/A	N/A	T9–L1	70°	31°	21°
Patient #13	No curve	N/A	N/A	N/A	T10–L2	50°	8°	13°

They found that the growth rate of vertebrae within instrumentation levels, which are mostly lower thoracic or upper lumbar vertebrae, was greater than their lower lumbar counterparts lying outside instrumentation levels.

In our study, the utilization of posterior tethering with distraction rods during the phases of growth potential is found to help decrease the pressure on the highly stressed parts of the growing vertebrae. Hypothetically, the vertebrae will remodel to retain their normal morphological structure; the remodeling of the vertebral morphology and the improved spinal alignment is expected to allow for maintenance of the spinal curve correction after the removal of the instrumented implants [25], which needs more clinical studies to prove that.

In our study, the average postoperative spinal length gain was 2.11 cm which showed comparable results with study done by El-Hawary et al. [26].

Advantages of this technique:

Table 5 Mean values of the investigated parameters in all patients

	Scoliosis Cobb	Spinal length (mm)	Kyphosis Cobb	AVBH	PVBH	AVBH/PVBH ratio (WICL)	AVBH/PVBH ratio (OICL)
Pre-op	52.75°	232.7	57°	6.58 mm	12.01 mm	0.54	0.76
Post-op	33.5°	253.8	23°				
Last follow-up	40.6°	274.8	21.1°	11.03 mm ($P < 0.001$)*	14.22 mm ($P = 0.001$)*	0.77 ($P < 0.001$)[#]	0.79

AVBH anterior vertebral body height, *PVBH* posterior vertebral body height, *AVBH/PVBH ratio* the ratio between anterior vertebral body height and posterior vertebral body height, *(WICL)* within the Instrumentation Compression Level, and *(OICL)* outside the Instrumentation Compression Level

* Paired *t* test was used to compare the pre-op and follow-up values of AVBH and PVBH

[#] Wilcoxon sign test was used to compare pre-op and follow-up values of AVBH/PVBH ratio results

1. Tethering effect through posterior approach.
2. Fixation of the rod in the center of the deformity without fusion will improve the rigid fixation [27].
3. The distance from the rod to the apex of the spinal deformity is minimal which will give more efficiency to compression.
4. No direct compression on the intervertebral disc.
5. It goes with the structural geometry of the spine.
6. Neurocentral synchondroses are not affected by this technique.
7. Adding hybrid construct with tethering will decrease the incidence of overcorrection [28].

Also, the study investigated human spines where gravitational forces affect the deformity and its correction process along with growth vertebral changes, which is more representative than animal models.

This study has some limitations which have to be pointed out. First, larger numbers of patients are required to strengthen the statistical significance. Also, there was a substantial heterogeneity in the cohort with respect to the patients' ages at surgery, diverse associated pathologies, and angular curvature.

Using plain X-rays instead of CT scans in the study may seem a drawback. Since our study involves measuring parameters of the vertebral body only, there might be no significant difference between X-ray and CT scans [29]. It can be speculated that the effect of the posterior tethering technique on vertebral growth and modulation would be better evaluated after the skeletal maturation is completed. Also, investigation of intervertebral discs and histological examination could not be done in our study.

Conclusions

Since this surgical technique utilizes a single posterior approach with minimal manipulation, this may make the posterior tethering technique a promising alternative, thereby decreasing the demand for anterior approach and/or osteotomies in these cases, and may stabilize the spine with the modulation (reversed domino).

Compliance with ethical standards

All procedures done in this study were within approved ethical standards.
Informed consent was obtained from all participants involved in this study.

Conflict of interest All authors declare that they have no conflict of interest.

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