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A new understanding of the mechanical mechanism of posterior vaginal prolapse based on magnetic resonance imaging

Qiaoling Shi[1], Zhongyuan Qiu[1], Yanfeng Song[2], Tongfei Wang[1],
Yan Li[1], Qiulan Dai[1] and Peifang Chen[1]

[1]Department of Obstetrics and Gynecology, Fujian Medical University Union Hospital, Fuzhou, China
[2]Department of Obstetrics and Gynecology, 900th Hospital of PLA, Fuzhou, China

ABSTRACT

According to the theory of force translation, the mechanical mechanism underlying posterior vaginal prolapse (PVP) can be speculated upon by measuring the displacement of the pelvic floor supporting structures with magnetic resonance imaging (MRI). Displacement of the posterior vaginal vault (Vp), the square root of the area under the curve between the sacrococcygeal inferior pubic point line (SCIPP) and the middle third of the posterior vaginal wall (PVW) (Sc′), the midperineal body (mid-PB), the H line, the M line, the estimated levator ani subtended volume (eLASV) and the levator hiatus width (LHW) were measured while participants performed during the Valsalva maneuver on MR images. These measurements were evaluated at different stages of PVP (n = 10, 12, 9, and 17 for stages 0, I, II, and ≥ III, respectively) with one-way analysis of variance (ANOVA), and the displacement difference ratio was used to describe the distribution process of force transfer. In Phase 1, the displacement difference ratios of Vp and Sc′ far exceeded those of mid-PB and eLASV; in Phase 2, the displacement difference ratio of eLASV increased significantly to more than ten times that of in Phase 1, whereas the displacement difference ratio of the mid-PB was unchanged; in Phase 3, the mid-PB displacement difference ratio increased by nearly 33 times that in Phase 2. Specific interactions between the pelvic floor muscles and connective tissues may occur during the course of PVW prolapse.

Keywords: posterior vaginal prolapse, supporting structure, magnetic resonance imaging, displacement differences, mechanical mechanism

Abbreviations:
MRI: magnetic resonance imaging
PVP: posterior vaginal prolapse
LAM: levator ani muscles
PB: perineal body
POP-Q: pelvic organ prolapse quantification
Vp: posterior vaginal vault
eLASV: estimated levator ani subtended volume
Sc′: the square root of the area under the curve between the sacrococcygeal inferior pubic point line and the middle third of the posterior vaginal wall

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Corresponding Author: Zhongyuan Qiu, MD
Department of Obstetrics and Gynecology, Fujian Medical University Union Hospital,
No. 29, Xinquan Road, Fuzhou 350001, China
Tel: +86-15980272755, Fax: +86-059186218003, E-mail: Qiuzhongyuanshd@hotmail.com

PVW: posterior vaginal wall
GH: genital hiatus

INTRODUCTION

The etiology of posterior vaginal prolapse (PVP) is closely associated with mechanical factors, and the three-level support theory describes the respective contributions of various vaginal supporting structures. According to theoretical biomechanical studies, the levator ani muscle (LAM) and other supportive systems (cardinal, uterosacral, paravaginal, and the perineal body [PB]) maintain the pelvic organs in their intended positions.[1,2] Although the application of finite element analysis has significantly enhanced our understanding of the underlying mechanical mechanisms of pelvic floor prolapse, it remains a digital simulation performed under ideal conditions that primarily involves the LAM and reflects anterior vaginal wall prolapse.

PVP is frequently considered to occur due to defects in the rectovaginal septum, and in clinical practice, surgical treatment is typically considered for strengthening these defects. However, recent surgical findings have shown a higher prevalence of defects at the vaginal vault (level 1) and vaginal introitus (level 3) than at the mid-vagina level (level 2) in cases of PVP.[3] According to current anatomical knowledge, losing any or all vaginal supports structures causes PVP.[4] Therefore, there is considerable debate on the importance of the pelvic floor muscles[5,6] and connective tissues[7,8] in managing PVP.

Given the increased use of magnetic resonance imaging (MRI), the understanding of PVP is improving. The normal pelvic anatomy can be identified on MRI,[9] which can also be used to record the clinical occurrence of rectocele and enterocele.[10,11] On MRI, changes in the movements of PVP have also been identified.[12,13] MRI investigations allow researchers to understand the mechanisms producing PVP and discern the relationship between the intra-abdominal pressure and the supports of the posterior vaginal wall (PVW) in inducing structure deformation.[14]

To date, although some findings on the biomechanical assessment of LAM has been published,[15] the pressure in different pelvic regions in vivo is still unknown. Using the concept of force-displacement-vectors,[16] we sought to identify the specific interactions between the pelvic floor muscles and connective tissues during the progression of PVP through the displacement differences between pairs of neighboring stages of PVP on MRI.

MATERIALS AND METHODS

Thirty-eight women diagnosed with PVP according to the pelvic organ prolapse quantification (POP-Q) system and divided into three groups according to the stage of POP[17]: stage I patients (n = 10), stage II patients (9), and stage ≥ III (12). A group of ten participants with normal vaginal support (stage 0, n = 10) was also included. Dynamic MRI scanning was performed on all of the subjects. Patients diagnosed with enterocele and a history of hysterectomy or other pelvic floor dysfunction surgery were excluded. Patient demographics, smoking status, vaginal parity, previous forceps midwifery, menopause status, hormone-replacement therapy (HRT) status, and Point D and B according to the POP-Q system were collected. This study was conducted in accordance with the declaration of Helsinki. This study was conducted with approval from the Ethics Committee of Fujian Medical University Union Hospital (2020KJT041). Written informed consent was obtained from the participants.

A Siemens Magnet Trio 3.0 T System (Siemens, Munich, Germany) was used to obtain static MR images in the coronal, sagittal, and axial planes with the patient in the supine position. The 3D-T2 sequencing parameters used in this study were described previously.[14] Prior to dynamic scan acquisition, the participants were guided to carry out a complete and repeated maximal Valsalva maneuver. The same urogynecologists and radiologists involved in the static MRI acquisition performed the structural identification.

The sacrococcygeal inferior pubic point line (SCIPP, x-axis) and the line perpendicular to it (y-axis) in the midsagittal plane were employed to correct discrepancies in pelvic inclination recorded at different positions throughout the scans.[18,19] The following structure locations were selected to represent the supporting structures at different levels: the posterior vaginal vault (Vp) for level 1, the square root of the area under the curve between the SCIPP and the middle third of the PVW (Sc′) for level 2, and the mid-PB for level 3. Moreover, the LAM was represented by the H line (the distance from the pubis to the posterior anal canal), the M line (the descent of the levator plate from the pubococcygeal line), and the levator hiatus width (LHW). During the Valsalva maneuver, the Vp, Sc′, the mid-PB, the H line, the M line, and LHW were measured at different stages for each subject (Figure 1). The estimated levator ani subtended volume (eLASV) was calculated via a method described in a previous paper.[20] The displacement differences ratios for Vp, Sc′, mid-PB and eLASV were calculated as the displacement difference between two consecutive stages divided by the displacement from rest to the Valsalva maneuver among stage 0 participants.

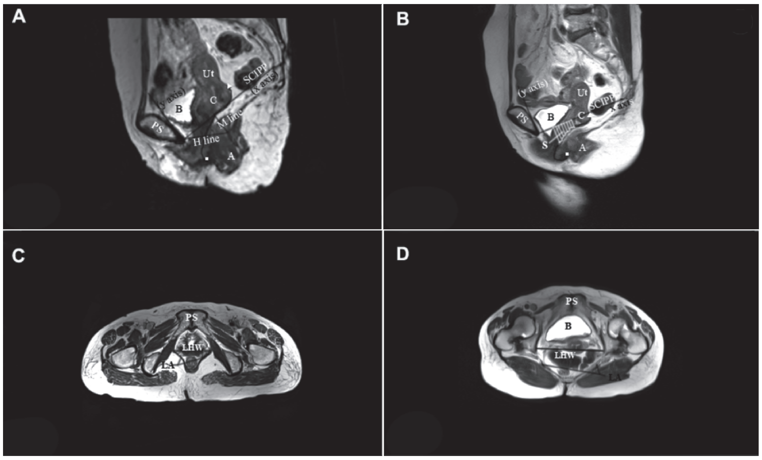

Fig. 1 Measuring the pelvic floor of a subject in the midsagittal and axial planes

Fig. 1A: Midsagittal MR image in the resting state showing the SCIPP and the PS along with the Vp (white triangle) and mid-PB (white square). The H line was drawn between the posterior wall of the anorectal junction and the inferior rim of the pubis at the level of the impression of the puborectal sling and the M line was drawn perpendicularly from the posterior wall of the anorectal junction to the SCIPP.

Fig. 1B: Midsagittal MR image at maximum Valsalva: Sc′ (white streak area) was calculated with the middle third of the PVW perpendicular to the SCIPP.

Fig. 1C: Axial MR image at rest, the LHW is measured at the bottom of the PS.

Fig. 1D: Axial MRI plane at maximum Valsalva maneuver.

Ut, uterus; C, cervix; B, bladder; A, anal canal; MRI, magnetic resonance imaging; LA, levator ani; SCIPP, sacrococcygeal inferior pubic point line; PS, pubic symphysis; Vp, posterior vaginal vault; PB, perineal body; PVW, posterior vaginal wall; LHW, levator hiatus width; Sc′, the square root of the area under the curve between the SCIPP and the middle third of the PVW.

Statistical analysis was performed with IBM SPSS version 21.0 (IBM). The data are presented as the means ± SDs, and the normality of the distributions was determined with the Kolmogorov–Smirnov test. Comparisons between groups were performed with the chi-square test and one-way analysis of variance. $P<0.05$ was considered to indicate statistical significance.

RESULTS

Table 1 displays the demographic data for all the subjects. The groups were similar in terms of age, vaginal parity, previous forceps delivery, menopausal status, HRT use, body mass index (BMI), and smoking status; the study population included only one woman who had smoked in the past and four women who were on HRT. Points D and B on the clinical POP-Q system differed significantly among the groups.

Table 1 Clinical characteristics across posterior vaginal prolapsed cohorts

Characteristics[a]	Stage 0 (n = 10)	Stage I (n = 12)	Stage II (n = 9)	Stage ≥ III (n = 17)	P value
Age, y	55.7±9.3	63.6±12.3	67.2±10.3	63.7±12.0	0.206[b]
BMI, kg/m^2	22.9±2.7	23.9±2.1	22.9±2.3	22.9±2.8	0.745[b]
Vaginal parity	2.7±0.9	3.3±1.2	3.0±1.2	3.6±1.3	0.271[b]
Rate of forceps midwifery, n (%)	0 (0%)	1 (8.3%)	2 (22.2%)	6 (35.3%)	0.098[c]
Post-menopause, n (%)	8 (80%)	8 (66.7%)	8 (88.9%)	13 (76.5%)	0.683[c]
HRT, n (%)	1 (10%)	0 (0%)	0 (0%)	3 (17.6%)	0.275[c]
Smoking, n (%)	1 (10%)	0 (0%)	0 (0%)	0 (0%)	0.317[c]
Aa point, cm	–2.6±0.5	–2.5±0.5	–2.4±0.7	–0.9±1.2	<0.001[b]
Ba point, cm	–2.8±0.4	–2.7±0.5	–2.1±1.0	1.7±1.3	<0.001[b]
C point, cm	–5.7±0.8	–5.3±0.6	–2.4±1.5	1.7±1.0	<0.001[b]
Ap point, cm	–2.2±0.6	–2.3±0.5	–1.8±0.4	1.5±0.9	<0.001[b]
Bp point, cm	–2.9±0.1	–1.7±0.5	–0.2±0.8	3.3±1.4	<0.001[b]
D point, cm	–7.9±0.8	–6.2±0.8	–4.9±0.7	–3.3±2.5	<0.001[b]
GH, cm	4.2±0.9	4.7±0.5	5.7±1.0	7.3±0.9	<0.001[b]
PB, cm	3.1±0.7	3.0±0.6	2.9±0.8	2.5±0.6	0.098
TVL, cm	7.8±1.4	7.9±1.1	7.3±1.0	7.8±1.5	0.798

[a] Values reported as either mean ± SD, or percent (where indicated).

[b] P values comparing group means were determined by one-way analysis of variance (ANOVA).

[c] P values comparing constituent ratios were determined by Chi-square test.

BMI: body mass index
HRT: hormone replacement therapy
GH: genital hiatus
PB: perineal body
TVL: total vaginal length

Table 2 shows the mean displacement of each support structure during the maximal Valsalva maneuver. The displacements of Vp, Sc′, mid-PB, and eLASV were different across groups ($P<0.05$), whereas those of the H line, M line, and LHW were not different ($P<0.05$). Figure 2 shows plots of the displacements versus stage for the various supporting structures; the figure shows that each displacement increased with increasing stage. To systematically characterize the progressive nature of PVP development, we have established a three-phase classification framework between each nodal point (stage 0 to stage ≥ III): progression phases were defined as Phase 1 (stage 0→I), Phase 2 (stage I→II), and Phase 3 (stage II→≥III). The proposed phase-based classification, though requiring careful interpretation, enables meaningful comparison of tissue-level interactions across PVP progression stages. Its stratification derives from evidence-based therapeutic protocols corresponding to distinct prolapse grade. The slope of each line in the different phases varied greatly from measurement to measurement. For example, the slopes changed notably for the displacement of Vp but only slightly for that of Sc′ over successive stages. Moreover, the slopes of the displacement of eLASV in Phase 2 and of mid-PB in Phase 3 were extremely high magnitude independently.

Table 2 Variation of various clinical parameters related to posterior vaginal prolapsed

Parameters[a]	Stage 0 (n = 10)	Stage I (n = 12)	Stage II (n = 9)	Stage ≥ III (n = 17)	P value[b]
Vp (mm)	16.70±8.56	22.56±16.28	27.89±16.76	39.24±16.88	0.003
Sc′ (mm)	6.37±4.10	9.14±4.25	10.64±7.17	15.22±6.55	0.004
mid-PB (mm)	18.98±9.03	21.46±9.02	21.77±9.73	33.17±8.45	0.000
eLASV (mm)	10.84±8.51	12.12±9.28	24.66±16.34	30.07±29.06	0.042
H line (mm)	5.48±4.18	6.35±2.95	10.43±7.78	10.19±6.70	0.092
M line (mm)	3.20±5.33	1.73±3.38	6.63±4.57	9.18±13.70	0.140
LHW (mm)	3.23±2.11	5.48±5.57	9.11±7.68	11.24±10.62	0.057

[a] Values reported as either mean ± SD.

[b] P values comparing group means were determined by one-way analysis of variance (ANOVA).

Vp: the posterior vaginal vault

Sc′: the square root of the area under the curve between the sacrococcygeal inferior pubic point line and the middle third of the posterior vaginal wall

PB: perineal body

eLASV: estimated levator ani subtended volume

H line: the distance from the pubis to the posterior anal canal

M line: the descent of the levator plate from the pubococcygeal line

LHW: levator hiatus width

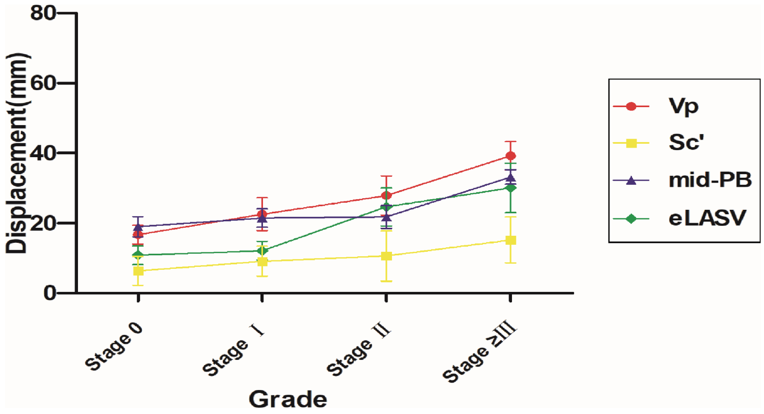

Fig. 2 Variation of various clinical parameters related to posterior vaginal prolapsed
Change curve of the average displacement of Vp, Sc′, mid-PB, and eLASV during different stages (standard deviation shown); * indicates a significant difference across the groups. $P<0.05$.
Vp: posterior vaginal vault
PB: perineal body
eLASV: estimated levator ani subtended volum
Sc′: the square root of the area under the curve between the SCIPP and the middle third of the posterior vaginal wall

Table 3 depicts the ratios of the displacement difference of the different support structures in distinct phases. In Phase 1, the displacement difference ratios of Vp and Sc′ far exceeded those of mid-PB and eLASV. In Phase 2, the displacement difference ratio of the eLASV increased significantly to more than ten times that of Phase 1. However, the displacement difference ratio of the mid-PB remained at approximately the same level as in Phase 1. In Phase 3, the displacement difference ratio of the mid-PB increased by nearly 33 times that in Phase 2.

Table 3 Ratio of the displacement differences

	Phase 1 (*stage 0–I*)	Phase 2 (*stage I–II*)	Phase 3 (*stage II–≥III*)
Vp	47.5%	27.1%	34.7%
Sc′	22.4%	7.6%	14.0%
Mid-PB	20.0%	1.6%	34.8%
eLASV	10.3%	63.7%	16.5%

Vp: posterior vaginal vault
Sc′: the square root of the area under the curve between the sacrococcygeal inferior pubic point line and the middle third of the posterior vaginal wall
PB: perineal body
eLASV: estimated levator ani subtended volume

DISCUSSION

In this study, the subtle changes in the load-bearing capacities of the supporting structures between two adjacent stages of PVP were reflected by calculating the displacement difference ratio on MR images according to the principles of force displacement principle and mechanical energy conservation. In this way, the detailed relationship of "cooperation and competition" between the pelvic floor muscles and connective tissues was quantified during the course of PVP.

Suppose that the intra-abdominal pressure is constant for each individual across the various stages of PVP and equals the sum of the pressure bearing on each supporting structure. When the supporting structures are damaged, the overall bearing force decreases, and the excess pressure is transformed into deformation according to the law of the conservation of mechanical energy. Therefore, information on the pressure transferred to each supporting structure throughout successive stages of PVP should be acquired by measuring their displacement difference ratios.

In Phase 1, the displacement difference ratios of Vp and Sc′ shifted far beyond those of the mid-PB and eLASV. However, considering the slight difference in clinical signs between stage I and stage 0 patients, we should consider the physiological range of motion[21] of the "visceral ligament".[22] When subjected to minimal force,[23,24] the main connective tissues at level 1, the cardinal and uterosacral ligaments can be "stretched." Therefore, the high movement of level 1 and level 2 cannot mean that these ligaments bear most of the pressure.

In Phase 2, the displacement difference ratio of eLASV increased significantly to approximately ten times that of Phase 1, but the ratio of mid-PB barely changed. This finding suggests that the LAM resisted most of the abdominal pressure passing from the top down. Despite the apparent increase in the levator hiatus (LH) and genital hiatus (GH), the remaining pressure was insufficient to make the bulging due to the prolapse noticeable. Since the bulging was not as clearly visible in stages I and II, we call this the 'implicit' bulging for the first time. These findings may also support the clinical treatments recommended by the most recent guidelines,[24] including the recommendation of pelvic floor muscle training as a first-line therapeutic option for women with POP-Q stage I or most cases of stage II over surgery.

In Phase 3, the displacement difference ratios of Vp, Sc′, and eLASV all increased compared with those in Phase 2, but the increase in the mid-PB was the most substantial (33 times). This finding seems to support the notion that most of the pressure is currently being placed on level 3 supports. When the stability of the PB begins to decrease, the support becomes unstable. Another finding was that the changes in LH and GH are similar to the findings of Dunivan et al,[25] who concluded that GH could be a sign of delitescent pelvic muscle damage. In other studies, a larger increasing GH size was considered closely related to apical vaginal support loss.[26] Hence, we concluded that level 3 supports start to bear more strain after stage II, when the upward support role of the LAM is overloaded. Ultimately, all the connective ligaments can no longer resist the force, the LH becames a 'release valve' for the pressure, the GH increases, and the bulging becomes 'explicitly.'

Surgical intervention has been incorporated into the multimodal therapeutic approach for POP-Q stage III or greater, as well as select stage II cases presenting with severe symptomatic manifestations. As a result, the relevance of PB repair was emphasized in our research. Many surgeons, such as Rovner et al[27] and Farroha et al,[28] believe that the perineal musculature, pelvic floor and PVW fascia can be properly repaired to rectify PVP.

However, no credible studies have yet been found to support this notion. Future research should focus on the real mechanical behaviors of these special structures in vivo, for example, by using cutting-edge technology or equipment, which will likely provide a new perspective for understanding the mechanical behaviors of the supporting structures.

As a result, the limitations of this study, like any other, should be noted. Given the small sample of selected subjects with PVP, the results therefore do not represent that it would occur universally among the population, and future investigations with larger cohorts are needed to validate these observations. Although our findings matched Haylen's opinion on the sites of pressure injury that can be evaluated from various anatomical perspectives,[25,29] any differences in our opinions were unavoidable due to displacement variations obtained directly from the MRI data. The real force-displacement relationships should be depicted by acquiring the biomechanical characteristics of different tissues in vivo. Meanwhile, the vaginal wall and neighboring organs should be considered during the load-bearing process, as the results would be more compatible with the biomechanical changes seen here. Just as many women with a PVP diagnosed on defecography but not have one clinically, the biomechanical characteristics in vivo remained under exploration. So our understanding of the PVW remains consistently inconsistent.[30] In contrast, MRI provides superior anatomical visualization, enabling more objective quantification of pelvic structures. Future studies incorporating multimodal diagnostic approaches may yield more definitive conclusions. Moreover, the removal of a fraction of the mechanical energy by tissue and organ changes might have affected mechanical mechanism, and the influence of other factors (eg, age, childbirth history, genetic elements) may bias the interpretation of the results. Finally, since other mechanisms could also lead to defect at level 1, eg, enterocele may result from a ventral shift of vaginal axis, so the conclusion of this study could no explain all situations.

CONCLUSION

In conclusion, the current study systematically presented a "tug of war" between the pelvic floor muscle and connective tissues in the course of PVP by quantifying displacement differences on the basis of MRI. This mechanical conceptualization, though containing unavoidable simplifications, offers critical insights into PVP progression given existing technological and empirical constraints.

DECLARATIONS

Authors' contributions

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

(1) Qiaoling Shi and Zhongyuan Qiu conceiving and designing the study;

(2) Qiaoling Shi, Zhongyuan Qiu, Yanfeng Song, Tongfei Wang, Yan Li, Qiulan Dai and Peifang Chen collecting the data;

(3) Qiaoling Shi, Zhongyuan Qiu, Yanfeng Song, Tongfei Wang, Yan Li, Qiulan Dai and Peifang Chen analyzing and interpreting the data;

(4) Qiaoling Shi writing the manuscript;

(5) Zhongyuan Qiu providing critical revisions that are important for the intellectual content;

(6) All authors approving the final version of the manuscript.

Conflicts of interest

All authors declare that they have no conflicts of interest.

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