Cardinal and deep uterosacral ligament lines of action: MRI based 3D technique development and preliminary findings in normal women

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Abstract

Introduction and hypothesis The cardinal ligament (CL) and deep uterosacral ligament (US) play a critical role in utero-vaginal support. This study aims to quantify their geometrical relationships in living women using a MRI-based 3D technique.

Methods The angles between ligaments, the ligaments length and curvature were assessed on 3D models constructed from twenty MRIs of volunteers with normal support. How angle variation theoretically affects ligament tension was investigated using a simplified biomechanical model.

Results The CLs are $18.1^{\circ} \pm 6.8^{\circ}$ (SD) from the cephalic-caudal body axis, and the USs are dorsally directed and $92.5^{\circ} \pm 13.5^{\circ}$ from the body axis. The CLs are longer and more

curved than US. The theoretical calculated tension on CL is 52 % larger than that on US.

Conclusions The CL is relatively parallel to the body axis while the US is dorsally directed. The tensions on these ligaments are affected by their orientations.

Keywords Cardinal ligament · Uterosacral ligament · Pelvic organ prolapse · Apical support

Introduction

Pelvic organ prolapse is a common and distressing condition that greatly affects women's daily activities and quality of life [1]. Thirty seven percent of women presenting for routine gynecologic care have prolapse stage II and above [2]. Prolapse is anticipated to increase in prevalence with our aging population [3, 4]. Despite the apparent prevalence of this condition, the underlying disease mechanism involved in causing prolapse is still poorly understood.

Recently, studies have revealed the central importance of apical support in holding the pelvic organs in place. Strong correlation between apex descent and prolapse size has been established in POP-Q exam [5], dynamic MRI study [6] and biomechanical modeling studies [7, 8]. Anatomically, apical support is provided by the combined action of the cardinal and uterosacral ligaments [9]. The structure of these ligaments has been described based on cadaveric dissections and cross-sectional anatomy [10–12]. These studies have provided some understanding of the structures' histological makeup and connections to the pelvic walls. However, for tension-based structures such as ligaments, knowing the spatial orientation of their lines-of-action is critical to understanding how they respond to increases in the loads they

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must resist. At present, data concerning the angles at which these ligaments act in living women is still not available.

The aim of this study is to quantify geometrical relationship between cardinal and deep uterosacral ligaments in living healthy women with normal pelvic floor support using a newly developed a MRI based 3D technique. In addition it investigates how variation in inclination of cardinal and deep uterosacral ligaments affect the tension in each ligament as it supports the pelvic viscera using a biomechanical model.

Methods

Twenty MRI scans from asymptomatic volunteers with normal support were sequentially selected from women recruited from the community to be in the control group of an on-going University of Michigan institutional review board-approved (IRB # 1999–0395), case–control study of pelvic organ prolapse. They were all asymptomatic based on Pelvic Floor Distress Inventory and Pelvic Floor Impact Questionnaires, had negative full bladder stress tests, and had pelvic organ support on POP-Q examination where all points lie within the normal range above the hymen as determined from population data [13]. As described in our previous studies [14], standard

anatomical scans made at rest, turbo spin echo (TSE) technique were used to image the sagittal, coronal and axial planes using a 3 Tesla Philips Achieva scanner (Philips Medical Systems, Best, The Netherlands) with a 6-channel, phased array, coil. 30 images were obtained in each plane (repetition time [TR] range, 2,300–3,000 ms, echo time [TE] 30 ms, 4-mm slice thickness, 1-mm gap, number of signal averages—NSA 2, 256×256 voxels, field of view 20×20 cm).

Axial and coronal MR-images were imported into a three-dimensional (3-D) imaging program (3-D Slicer3, version 3.6) and aligned using bony anatomic landmarks. The uterosacral ligaments visible in MR have band-like appearance and were identified [15] and traced on axial MR images from its origins at the sacrum and pelvic floor to its insertion onto the lateral margin of the upper vagina and cervix (Fig. 1). These represent the deep uterosacral ligaments defined by [16] that are the portion of the ligament under the rectovaginal peritoneum which is thicker and denser and can be identified on MR images. Cardinal ligament was identified as web-like aspect centered around the axis of the internal iliac (anterior trunk) vessels [17] and traced on coronal MR images (Fig. 2) from points of origin at the top of the greater sciatic foramen at the sacro-iliac articulation. These points were chosen due to its consistent visibility and its location at the top of the greater sciatic

Fig. 1 Axial MR slices at 5 mm intervals arranged caudal to cephalad starting from the image in the upper left. Slice location relative to the arcuate pubic ligament (e.g. -0.5) are shown in the lower right corner of each images. Deep uterosacral ligament tracings were made in dashed

outline. The center of the uterosacral ligament insertions to vagina, cervix, sacrospinous ligament and coccygeus muscle were marked in red dots. B: bladder; Vag: Vagina; Cx: Cervix; R: Rectum

Fig. 2 Coronal MR slices at 5 mm intervals arranged ventral to caudal starting from the image in the upper left (Image -0.5 cm, image level 0 is at where the cervix is). Cardinal ligament regions were outlined and

origins at the top of great sciatic foramen and insertions to the genital tract were marked in red dots. B: bladder; Vag: Vagina; Cx: Cervix; R: Rectum

foramen where the cardinal ligament is anchored. The points of deep uterosacral ligament insertion on the cervix and upper vagina were made at the lateral margin of the genital track at the cervix and upper vagina.

The 3D slicer models and anatomical landmarks were imported into Imageware v.12© (UGS, Plano, TX) (Fig. 3); an engineering analysis software that allows complex 3D models to be quantified. The 3-D lines-of-action of the four ligaments were determined by connecting center of the origin and insertion points (Fig. 3b, c). The angles between the cardinal and deep uterosacral ligament on each side, and the angle between the left and right cardinals and between the left and right deep uterosacral were measured. To measure the length and curvature of these ligaments, a cross-section was constructed in the model for each ligament by cutting the model with a plane defined by its line-of-action and genital origin point of opposite side. The best fit curve of the ligament was constructed by connecting the center line of the cross-section. The length, distance between origins and insertions, and curvature of the ligaments measured as tangent direction difference were assessed (Fig. 3). The body axis was taken to be the cephalic-caudal axis parallel to the scan table.

A simplified four-cable suspension biomechanical model was constructed to estimate the tension on each ligament when they are subjected to pelvic loading (Fig. 4). In this

model, we represented the actions of the left and right deep uterosacral ligaments and left and right cardinal ligament by four cables (whose tensions are designated as Tu^L , Tu^R , Tc^L , Tc^R). Since data concerning the actual force on the ligaments is unknown we have arbitrarily set as unit loading at 1 Newton [N] recognizing that actual loads will be proportional to that load (i.e. a 2 newton load will have twice the values for each ligament). This load was placed on the ligaments following the average angle of the levator plate (Fig. 4) whose angle was set at 44° from the horizontal (using MRI measurements of women with normal support, [18]); a direction that is consistent with movement toward the vaginal introitus. The proportions of the loading placed on the cardinal and deep uterosacral ligaments were calculated using these parameters. Secondary analysis was performed using levator plate angle (LPA) of 53° based on measurements of prolapse patients [18].

Results

The mean age of the 20 study participants was 58 ± 10 (SD) years, the mean body mass index (BMI) was 27.2 ± 4.1 (SD) kg/m^2 , while median parity was 2. They are mostly Caucasians (19 Caucasians and one Africa American). The POPQ of all women but one have all points at least 1 cm above

Fig. 3 Methodology to measure the length, curvature and the angles of the cardinal and deep uterosacral ligaments. Panel A: 3D models of pubic bone (PB), Sacrum (Sac), Uterus (Ut), Vaginal (Vag) and Cardinal ligaments (CL) and Deep uterosacral ligament (US) in three-quarter view. Panel B: Identification of origin-insertion line and best five curve for the cardinal ligament seen from the back. Red dots are the landmarks identified for origins and insertions. Blue line connects the center of landmarks to establish the line-of-action. The angle between

cardinal ligaments was measured as α . Red curve present the best fit curve of the ligaments on the cross-section showed as black line in the bottom. Length of the curve is l and the tangent direction difference was measured as Δ . Panel C: Deep uterosacral ligament line-of-action and best fit curve, angle between deep uterosacral ligament β was measured in axial plane. Panel D: Angles γ between cardinal and deep uterosacral ligament in sagittal plane. The blue lines presents the line-of-action of the ligaments

hymen (one woman with her anterior support at the hymen level). The 3D geometrical relationship between cardinal and deep uterosacral ligaments shows in Fig. 5 as projection angles to axial, coronal and sagittal plane. There is no difference in angles between cardinal and deep uterosacral

ligament in left and right side. The mean angle between cardinal ligament and body axis is $18.1^\circ \pm 6.8^\circ$ (SD), ranging from 7.8° to 35.1° . The mean angle between deep uterosacral and body axis is $92.5^\circ \pm 13.5^\circ$, ranging from 71.2° to 116.4° .

Fig. 4 Four-cable suspension biomechanical model. Left shows the MR-based 3D model of the uterus and vagina and transparent levator ani muscle (blue) with lines of action of cardinal and uterosacral ligaments in the side view. PS: pubic symphysis; Sac: sacrum. Right shows the simplified four-cable load-sharing biomechanical model free

body diagram. Pelvic load models the downward tension placed on cervix (Cx) resulting from increasing intra-abdominal pressure and is arbitrarily set to be 1 N and parallel to levator plate direction (levator plate angle, LPA). This force results in the tension on cardinal ligaments (Tc^L and Tc^R) and deep uterosacral ligament (Tu^L and Tu^R)

Fig. 5 Results of angular relationship between ligaments and its variation among a group of women. Solid line shows the median orientation of the ligaments. Light shadows indicate the range of the angle variation. Dark shadows with dashed line shows the orientations ranging from 25th to 75th percentile. Cx, cervix; CL, cardinal ligament; US: Deep uterosacral ligament; Sac: sacrum. **Panel A** shows the projection angle between cardinal ligaments on coronal plane. **Panel B** shows the projection angle between deep uterosacral ligaments on axial plane. Sac presents sacrum. **Panel C,D** shows the angles between cardinal and deep uterosacral ligament on both left and right side on sagittal plane

Cardinal ligaments are significantly longer than deep uterosacral ligaments ($P < 0.001$) (Table 1). Left and right cardinal ligament has similar length while right deep uterosacral ligament is about 29 % longer than that in the left side. Both cardinal and deep uterosacral ligament demonstrate their curved nature. Cardinal ligaments have larger curvature than that of deep uterosacral ligament measured as tangent direction difference of the best fit curve ($P < 0.001$).

The calculated tensions on cardinal and deep uterosacral ligament calculated by four-cable load-sharing biomechanical model were shown in Table 2. Using levator plate angle in women with normal support, the tensions in the cardinal and the deep uterosacral ligaments were 52 % higher in cardinal ligament than that of deep uterosacral ligament. Changes in the levator plate angle caused changes in the tension on the ligaments, a more vertical levator plate such as that in women with prolapse (53°) increases the calculated tension placed on

cardinal ligament by 17 % and decrease the tension on deep uterosacral ligament by 31 %.

Discussions

In this study we developed a technique to quantify the geometrical relationship between cardinal and deep uterosacral ligament at rest and accessed how the variation of their inclination affects the tension using a simplified biomechanical model. Our results reveal the average direction of these ligaments and describe their variation in women with normal support. The cardinal ligaments are relatively parallel to the body axis and are vertically oriented when a woman is upright, while the deep uterosacral ligaments are more dorsally directed toward sacrum. Their orientation relative to the direction of the force placed upon them affects their tension and their contribution to the load bearing. In a

Table 1 Length and curvature measurement of the ligaments

	Best Fit Curve Length (mm) Mean $\pm$ SD (Minimum ~ Maximum)	Tangent Direction Difference ($^{\circ}$) Mean $\pm$ SD (Minimum ~ Maximum)	Distance between Origins & Insertions (mm) Mean $\pm$ SD (Minimum ~ Maximum)
Cardinal Ligament (L)	55 $\pm$ 12 (37~76)	108.7 $\pm$ 34.1 (47.8~156.9)	47 $\pm$ 7 (35~57)
Cardinal Ligament (R)	58 $\pm$ 10 (42~74)	120.0 $\pm$ 21.2 (78.9~155.8)	48 $\pm$ 10 (33~60)
Uterosacral Ligament (L)	24 $\pm$ 9 (11~47)	54.6 $\pm$ 22.9 (17.6~103.5)	23 $\pm$ 9 (11~45)
Uterosacral Ligament (R)	31 $\pm$ 10 (14~49)	52.4 $\pm$ 33.1 (3.4~104.8)	30 $\pm$ 7 (17~44)

biomechanical model based on these angles, the cardinal ligament which is more aligned to the loading direction has a greater tension than the deep uterosacral ligament that is less aligned. Moreover, inter-individual ligament orientation varies widely. Therefore, there may be certain individuals who, because of their geometry, have ligaments subjected to greater tension for any given pelvic load.

This study adds new information concerning the relationship of two different components of apical support and how the orientation of the cardinal and deep uterosacral ligaments affects their contribution to the apical support. Apical support has been identified as an important fact in anterior vaginal wall support. Rooney et al. [5] reported a strong correlation between the apex and most prolapsed portion of the anterior vaginal wall, with a Spearman's correlation coefficient of 0.835. Summers et al. [6] showed that the variation in apical support contribute 60 % to the variation of cystocele size. Our group [7, 8] used simplified biomechanical models to study anterior vaginal wall support system and demonstrated the interaction between apical support, levator ani muscle function, paravaginal support and intra-abdominal pressure. This study adds important information by assessing the load sharing between different components of apical support. The deep uterosacral and

cardinal tissues are critical components of Level I support and provide support for the vaginal apex [9]. Neither are true ligaments in the sense of a skeletal ligament that are composed of dense regular connective tissue similar to knee ligaments. They are “visceral ligaments” that are similar to mesentery. They are made of blood vessels, nerves, smooth muscle, connective tissue and adipose tissue intermingled with irregular connective tissue that condenses along lines of tension [11, 12]. They have a supportive function in limiting the excursion of the pelvic organs much as the mesentery of the small bowel limits the movement of the intestine. When these structures are placed on tension, they form condensations of tissue that resist further displacement so they have come to be referred to by surgeons as ligaments [11, 12]. Our technique has defined the line-of-action of those ligaments while they are under tension by connecting the center of their anatomical insertions to genital track and insertions to the pelvis.

Both the cardinal and the deep uterosacral ligaments are visible from pelvic MR images. The cardinal ligament is a mass of retroperitoneal areolar connective tissue in which blood vessels predominate; it also contains nerves and lymphatic channels [12]. It has a configuration similar to that of “chicken wire” or fishing net in its natural state but when

Table 2 Calculated Tension on Cardinal and Deep uterosacral ligaments using four-cable model

	Tension on Cardinal Ligament Mean $\pm$ SD (Minimum~Maximum)		Tension on Uterosacral Ligament Mean $\pm$ SD (Minimum~Maximum)	
	Left (Tc ^L in Newton)	Right (Tc ^R in Newton)	Left (Tu ^L in Newton)	Right (Tu ^R in Newton)
Normal Support Levator Plate Angle 44 $^{\circ}$	0.43 $\pm$ 0.10 (0.33~0.67)	0.45 $\pm$ 0.08 (0.29~0.60)	0.27 $\pm$ 0.06 (0.19~0.43)	0.31 $\pm$ 0.10 (0.09~0.54)
Prolapse Levator Plate Angle 53 $^{\circ}$	0.49 $\pm$ 0.09 (0.40~0.70)	0.52 $\pm$ 0.08 (0.40~0.70)	0.19 $\pm$ 0.06 (0.06~0.32)	0.21 $\pm$ 0.09 (0.01~0.42)

placed under tension assumes the appearance of a strong cable as the fibers align along the lines of tension [12]. Because of its relatively vertical orientation, it is best seen on the coronal MR images. It is demarcated by the vessels and lymphatic elements lateral to the pelvic organs (Fig. 2). The deep uterosacral ligaments are bands of tissue running under the rectovaginal peritoneum composed of smooth muscle, loose and dense connective tissue, blood vessels, nerves, and lymphatics [11]. They originate from the postero-lateral aspect of the cervix at the level of the internal cervical os and from the lateral vaginal fornix [11]. Because of their relatively anteroposterior orientation, they are best seen in the axial scan images (Fig. 1). While macroscopic investigation observed insertion of the ligament to the levator ani, coccygeus, and the presacral fascia [10, 19], MRI examination showed the deep uterosacral ligaments overlies the sacrospinous ligament and coccygeus in 82 % of the cases and over the sacrum in only 7 % of the cases [15]. The difference between the appearance of these structures in MRI and on dissection may have to do with the tension placed on the structures during dissection and will require further research to clarify. Our technique established the best fit curves to represent cardinal and deep uterosacral ligaments in their resting state, and then measured their length and curvature. Left and right cardinal ligaments have similar length, while the deep uterosacral ligament in the right side is about 29 % longer than that of left side. Indeed, Umek et al. [15] found similar results with the left deep uterosacral ligament being shorter in its craniocaudal extent. Anatomically, this may be explained by the presence of the sigmoid and its mesentery in the left pelvis, thus leaving less space for the deep uterosacral ligament on that side. Furthermore, the asymmetric nature of the ligaments explains the dextro-rotation of the uterus observed during pregnancy.

Our length measurements of uterosacral ligament are shorter than those that have been made during dissection [19]. First, our measurements were based on the uterosacral ligament visible on MRI, which represents the deep neurovascular portion of the uterosacral ligament [16]. The superficial fibrous portion of uterosacral ligament [16] observed from the peritoneal cavity when the uterus is pulled anteriorly and placed under tension however is too thin to be able to consistently indentified and traced on MRI due to partial volume averaging artifact. Second, our technique measure ligament length in the resting status, while most of the dissection techniques measure these ligaments placed on maximal tension. There may also be some loss of smooth muscle tone of the cadaver. These factors may contribute to uterosacral ligament length between MR studies and cadaver study, further research is needed for clarification.

The study also showed that cardinal ligaments have larger curvature compared to the deep uterosacral ligament. Anatomically, larger curvature is necessary for cardinal

ligament rising from its genital insertions, wrapping around the pelvic organs and attaching to the pelvic sidewall. Functionally, this curvature provides the apex with certain range of motion. Larson's study [14] demonstrated apical descent during Valsalva in both women with and without prolapse with prolapse having a far greater degree of descent. Bartscht and DeLancey [20] measured the passive tissue support of uterus when asymptomatic patient under anesthesia, they found that there are more than 1 cm decent when cervix only subject to small amount of force (<1 lb). Our finding that cardinal ligaments has larger curvature agrees with those observations, by straightening curved cardinal ligaments it allows the certain apical descent without putting too much stress on the ligament.

The directions of the two elements mirror the different axes of two of the standard approaches to apical support. The suspension provided by abdominal sacral colpopexy is more vertically directed as is the cardinal ligament vector. The sacrospinous ligament suspension and McCall culdoplasty seems similar to the deep uterosacral ligament in its dorsal orientation towards the sacrum. It is interesting to speculate that the different results seen from the operations may reflect the fact that only one of the two vectors is addressed. In the senior author's experience with these two operations, after sacrospinous suspension anterior vaginal wall prolapse is the predominant location of postoperative support loss while with abdominal sacral colpopexy, it is the posterior vaginal wall that is more likely to fail. If one hypothesizes that the cardinal ligament is most influential in anterior compartment support and the deep uterosacral in posterior compartment support, then these different results can be inferred to occur from repairs that emphasize one or the other axis. These hypotheses will require more direct study to clarify these issues further.

Several factors should be considered in interpreting the results of this study. First, magnetic resonance images were obtained in the supine position, and standard anatomical scans at rest were used to establish the apical support vectors. Ideally, the apical support vector at maximum pelvic load in standing position would be measured and put into biomechanical model to study the load sharing. Although this has important theoretical implications, in practice there hasn't been shown differences in MR images acquiring in the upright seated position in open scanners when compared with images obtained supine [21, 22]. It is most likely because increased activity of the levator ani in the upright position to counterbalance the effects of gravity [23]. In addition, it would be ideal to obtain the MR images at the maximum Valsalva, however alignment of viscera in different planes to be able to reconstruct cardinal and deep uterosacral ligament is not currently possible due to the variable deformation of soft tissue with each Valsalva [24]. As scan resolution improves and scanning times decline, this should

become possible. We believe that the Valsalva loading will only have small changes in normal apical support vectors orientations, the apical support vector at rest did provide a baseline measurement for the first time and provide important insight of very different support vectors of cardinal and deep uterosacral ligament. Second, we use a simplified biomechanical model to theoretically analyze the tension on each ligament. Such models yield can useful mechanistic insights and has been used widely in biomechanics field [25], but need to continuously validate its results with the measurement from what happens in living women. In analysis of relative ligament tension, the loading to the apical support is simplified as a “pelvic load” (arbitrarily set at unit loading 1 Newton [N]) pulling the ligaments parallel to the levator plate direction. The proportional relationship of tension placed on cardinal and deep uterosacral ligament were studied but the actual magnitude still remain unknown. The direction and magnitude of pelvic loading to apex remain interesting research questions worthy further investigation.

The present technique to create 3-D models of cardinal and deep uterosacral ligament from MR images, establish ligaments line-of-action and simple suspension model to study load sharing greatly enhances our ability to study the mechanisms of apical support. Preliminary findings suggest cardinal is relatively vertical in standing position while the deep uterosacral is more dorsally directed. There is considerable variation in the angles for the cardinal and deep uterosacral ligaments in normal women and these angles affect ligament tension for any given load. The load supported by each ligament can be expected to vary depending on the angle between ligaments. It would be interesting to apply this technique for a case–control study and investigate whether there is a difference in the apical support vector between women with normal support and women with prolapse and then use the biomechanical model to interpret the effect of this difference.

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Conflict of Interest None.

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