Variations in levator ani volume and geometry in women: the application of MR based 3D reconstruction in evaluating pelvic floor dysfunction.

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Summary.- OBJECTIVE: We report on the comparative 3-dimensional (3D) living female pelvic floor geometry in five women, comparing the volume, morphology, and integrity of the levator sling, and pelvic anatomic relationships among study subjects.

METHODS: Five women of varying ages, parity, continence, and prolapse status were studied. Two-dimensional (2D) imaging of the pelvic floor organs was performed on each subject in the supine position. Manual segmentation techniques and solid modeling software was used to build 3D models of each patient’s pelvic floor structures, which could then be viewed and measured on the computer screen. We measured levator muscle volume, posterior urethro-vesical angle, distance from the urethra to pubo-coccygeal line, and the levator plate angle. The integrity of pubo-coccygeal attachments was also recorded.

RESULTS: Levator muscle volume ranged from 68ml in the nulliparous female, to 26ml in the grand multipara with severe prolapse and mild genuine stress incontinence (GSI). The second lowest volume (30ml) was in the multipara with GSI. Volumes in the parous subjects without stress urinary incontinence or pelvic organ prolapse were 36 and 39ml. Pubo-coccygeal attachments were found to be torn in the 2 symptomatic subjects, and were intact in all 3 asymptomatic subjects.

CONCLUSION: MR based 3D modeling is feasible and can be used in a research setting to evaluate complex anatomic relationships which may accompany pelvic floor dysfunction. The technique can also be used to evaluate levator muscle morphology and volume, as well as pelvic floor support integrity and its possible role in GSI and prolapse. We are currently conducting a larger study to validate our technique, and to better define the relationship between pelvic floor geometry and pelvic floor dysfunction.

Keywords: Three-dimensional modeling. Pelvic floor. Prolapse. Incontinence. Magnetic resonance imaging.

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Resumen.- OBJETIVOS: Presentamos los resultados de un estudio basado en la reconstrucción tridimensional de la geometría de la pelvis femenina en 5 mujeres, y se realiza un análisis comparativo del volumen, morfología e integridad del cabestrillo de músculo elevador del ano, así como las relaciones anatómicas en este grupo de pacientes.

MÉTODOS: Se evaluaron 5 mujeres de distintas edades, paridad, estado de continencia y prolapso. Se realizó un estudio bidimensional de los órganos pélvicos en posición supina en todas las pacientes. Se elaboraron mediante técnicas de segmentación manuales y un programa de reconstrucción para sólidos, los modelos tridimensionales de las estructuras pélvicas de cada pa-
ciente para su posterior visualización y medición sobre la pantalla del ordenador. Se analizaron los siguientes parámetros: volumen del músculo elevador del ano, ángulo uretrovesical posterior, distancia entre la uretra y la línea pubococcígea, ángulo del músculo elevador, así como la integridad de las inserciones pubococcígeas.

RESULTADOS: El volumen del músculo elevador osciló entre los 68 ml en las nulíparas y los 26 ml en las multíparas de varios embarazos, con prolapse severo e incontinencia urinaria de esfuerzo. Las multíparas con incontinencia de esfuerzo mostraron el segundo volumen más bajo (30 ml). Las mujeres que habían tenido uno o más partos, sin incontinencia urinaria de esfuerzo o prolapse de órgano pélvico, presentaron un volumen de 36 ml y 39 ml. Se demostró desgarro de las inserciones pubococcígeas en dos casos sintomáticos y la integridad de éstas en 3 casos asintomáticos.

CONCLUSIONES: La reconstrucción tridimensional es viable y puede emplearse en el contexto de la investigación para el estudio de las complejas relaciones anatómicas que podrían asociarse en la disfunción del suelo de la pelvis. Esta técnica también puede emplearse para evaluar la morfología y volumen del músculo elevador, así como en el estudio de la integridad de las estructuras de sostén del suelo de la pelvis y su posible papel en la incontinencia por esfuerzo y el prolapse. En la actualidad, estamos realizando un estudio más amplio para la validación de nuestra técnica y para conseguir una mejor definición de la relación entre la geometría y la disfunción del suelo de la pelvis femenina.


INTRODUCTION

Although many studies have been performed to unravel the mechanisms underlying the genesis of prolapse and genuine stress incontinence due to hypermobility (GSI), the role of the levator ani muscles remains poorly understood. Nonetheless, the levators remain the focus of many non-surgical therapies for the treatment of this condition, but with varying degrees of success (1).

Female stress urinary incontinence and pelvic floor prolapse is thought to be due to levator ani muscle, fascial and/or nerve damage incurred during childbirth trauma (2). When conservative therapy for GSI fails, surgical intervention is aimed at re-supporting the bladder neck (3). Commonly employed surgical procedures include the Burch colposuspension (4), bladder neck sling (5), needle urethropexy (6), and the Kelly plication (3). These procedures have reported complication rates of 6-32% (7), and failure rates of 3-40% (7, 8). Various surgical procedures have been advocated for repair of pelvic organ prolapse depending on the site of the defect (9). Despite surgery, prolapse can recur in up to 34% of cases (10). It is possible that the recurrences may be due to failure to identify the causative lesion in the pelvic floor prior to surgery. The causative lesion could be a site-specific fascial defect or even anatomic disruption of the levator ani muscles.

Conventional 2D magnetic resonance imaging (MRI) has been used to assess the anatomy of the female pelvic floor. Strohbehn et al., reported excellent correlation between cadaveric dissection and MRI findings (11). In living women, MRI has also been employed to correlate imaging findings with the presence of clinical pelvic floor dysfunction. Huddleston et al., reported three alterations in vaginal shape that were associated with pelvic floor prolapse (12). Kirschner-Hermanns et al., reported increased T1 signal intensity as evidence of muscle atrophy in 66% of their subjects with stress incontinence (13). Healy used MRI to show a statistically significant increase in cystoceles and recto-uterine prolapse in constipated subjects when compared to normals and those with fecal incontinence (14). When we investigated the value of MRI of the pelvis in the sitting position, we found a trend towards levator muscle laxity and thinning in women with stress urinary incontinence (15). However, it is possible that our results were a reflection of the wide normal range of levator muscle volume, and this bears further study. The disadvantage of 2D MRI stems from its inability to easily disclose the 3-dimensional relationships, which may be at the root of the defects, which lead to clinical pelvic floor pathology.

To better understand the specific anatomic defects that may be at issue here, we evaluated the morphology and volume of pelvic floor support muscles, and the bladder neck, using three-dimensional MR based models in 5 living women, with and without clinical pelvic floor pathology. The immediate goal was to demonstrate the feasibility of the technique of 3D pelvic floor modeling in various clinical settings.
MATERIALS AND METHODS

We evaluated a small group of subjects with a wide range of age, parity, prolapse, and continence status. One subject was chosen from each category. Inclusion criteria consisted of willingness and ability to tolerate an MRI scan, and ability to give informed consent. Exclusion criteria were prior pelvic or vaginal surgery (cesarean delivery, tubal ligations and laparoscopy excepted), and ferromagnetic implants. Accordingly, five women were selected to participate: three women without urinary incontinence; 1) a 35 y/o nullipara, 2) a 29-year-old primipara, 3) a 29-year-old multipara, and two with incontinence; 4) a 44-year-old multipara with GSI, and 5) a 75-year-old grand multipara with grade 4 vaginal vault prolapse and occult GSI. All subjects were asked if they had urine leakage with coughing or laughing. In those who answered affirmatively, diagnoses of GSI were made with the aid of multichannel urodynamic evaluation. Conventional 2D MRI studies were performed: T2-weighted source images were obtained in the axial and sagittal planes using a 1.5T magnet (General Electric Medical Systems, Milwaukee, WI) and a torso phased array coil wrapped around the pelvis. The following imaging parameters were employed: TR=4200msec, TE(eff) =108msec, 128 phase encodes, 24cm field of view, 3mm slice thickness, no gap, 2 acquisitions. The entire sequence was repeated adjusting the slice locations to obtain contiguous images 1.5mm in thickness. Total scanning time was approximately 19 minutes.

After the MRI acquisitions were completed, data was electronically transferred to a Sun UltraSparc-30 graphics computer workstation (Sun Microsystems, Mountain View, Ca). The data was first segmented into anatomically significant components, including bladder, urethra, uterus, vagina, rectum, muscles, and bones and then labeled using a combination of semi-automated and manual editing. The manual segmentation time was approximately 10 hours per subject. From these images, 3D renderings of the pelvic viscera as well as supporting muscle, fascia and bones were reconstructed using the marching cubes algorithm and a surface rendering method (16). Three-dimensional surface models were generated using a pipeline consisting of dividing cubes, triangle reduction, and triangle smoothing (17, 18). The

Fig. 1a: This figure shows the case of intact pubococcygeal attachments on the left and right (arrow).

Fig. 1b: This is the case where the left attachment is deficient and probably torn (black arrow). Here, the distance between the white and black arrows is the pubococcygeal gap (PCG).
computer time for 3D model generation was approximately 1.5 hrs per subject.

Volumes were computed by multiplying the number of volume elements (voxels) enclosed by the segmented 3D volume, by the voxel volume, which is the product of the picture element (pixel) area (0.8789 square mm in our series), and the effective slice thickness (1.5mm). To compute linear measurements, the user first defines a path of interest. The 3D Cartesian components (i.e., x, y, z) of the path are determined, and the resultant vector ( \( \mathbf{R} \) ) is the square root of the sum of the squares of each of the Cartesian components:

\[
\mathbf{R} = \sqrt{(x^2+y^2+z^2)}
\]

Angular measurements are obtained by defining the angle on the computer screen, and its value is computed by trigonometric analysis. The integrity of the pubococcygeal attachments is determined by measuring the pubococcygeal gap (PCG), i.e., the distance (in cm) from the most anterior aspect of each arm of the muscle to the nearest inferior aspect of the symphysis.

The final results were viewed on a workstation with graphics acceleration, and specialized measurement software was used to compute the linear and volume measurements of the on-screen renderings. Representative 2D axial slices are given in figures 1a and b. Examples of the 3D renderings are shown in figures 2 and 3, including definitions of the measurement parameters.

RESULTS

The subjects tolerated the MRI scans well. Good quality source images were obtained, and we were able to identify most of the structures of interest easily on the MR source images. The one exception was the gap in the pubic attachment of the pubococcygeus, which was difficult to identify completely in its most anterior-superior aspect from the axial slices. In this case, we traced the muscle as far anterior as it could be reliably identified. Segmentation of the structures, and conversion to 3D was routine. Computation of volume, linear, and angular measures were accomplished interactively, and recorded on a standardized form. Data storage required approximately 20 megabytes per subject, and was found to be adequate.

Quantitative results are given in Table I for the 3D models and Table II for the source images. Computed bladder volumes were 23 and 30.5cc in two of the...
subjects without GSI. In the nulliparous non-GSI subject, bladder volume was 148cc, but this elevated volume was probably due to her failure to void as instructed prior to the MRI study. In the GSI only patient, bladder volume was higher at 57cc, and it was 136cc in the subject with prolapse and occult GSI, the latter likely due to urinary retention caused by the buttressing action of a 10cm uterine fibroid which kinked this subject's bladder neck.

The length of the pubococcygeal line (PCL) varied from 87mm in the nullipara, to 107mm in the asymptomatic para3, without correlation to symptomatology. The distance from bladder neck to PCL was 13mm and 15.9mm in the nullipara and primipara, but increased to 22 – 23mm in the multiparous subjects.

The posterior urethro-vesical angle varied from 125 degrees in the asymptomatic multipara, to 173 degrees in the grand multipara with prolapse, without apparent correlation to symptomatology. The levator plate angle (LPA) was the most difficult parameter to estimate, owing to the curved shape of the median raphe, and we found that this parameter varied between 12 and 19 degrees in all subjects except the 29-year-old primipara, where it was 38 degrees.

The volume of the levator ani muscles ranged from 68ml in the nulliparous female, to 26ml in the grand multipara with severe prolapse and occult GSI. The second lowest volume (30ml) was in the multipara with GSI. Volumes in the parous subjects without stress urinary incontinence were intermediate at 36 and 39ml.

Our marker for pubic ligament attachment defects is the PCG. The measurements fell into 2 groups; less than 2cm in the 3 asymptomatic subjects, and >3cm in the 2 subjects with symptoms. Larger gaps (>3cm) may suggest torn ligaments and shorter gaps (<2cm) suggest an intact ligament. The prolapse subject showed a gap of 5.4cm on the right (suggestive of a tear) and 2.3cm on the left (borderline), and the GSI subject showed a gap of 3.1cm on the left, (suggestive of a tear), and a contralateral gap of 1.7cm (suggestive of an intact ligament). The asymptomatic patients all show gaps less than 2cm.

Finally, the maximal width of the levator hiatus was examined. With the exception of the 62mm finding in the grand multipara with prolapse, this parameter varied minimally in the 32 – 39mm range.

**CONCLUSION**

The present small study demonstrates the feasibility of using MR-based 3D reconstruction to study the levator ani as a determinant of pelvic floor dysfunction. Even though our results are drawn from a small number of subjects, it is interesting to note that, from these preliminary results, levator volume was highest in the premenopausal nulliparous woman, and substantially lower in a primiparous subject of similar age. Both of

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**TABLE I. Measured parameters from the reconstructed 3D models. (GSI – Genuine stress incontinence, SVD – spontaneous vaginal delivery, UI – Urinary incontinence)**

<table>
<thead>
<tr>
<th>Patient</th>
<th>Bladder vol (cc)</th>
<th>Pubo Coccyx Line (PCL mm) (A)</th>
<th>Bladder neck – PCL (mm) (B)</th>
<th>Post UV angle (deg) (angle C)</th>
<th>Levator plate angle (deg) (angle A-D)</th>
<th>Levator vol (cc)</th>
<th>Max Width Levator Hiatus(mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>28 y/o Nullipara, no UI (Premenopausal)</td>
<td>148</td>
<td>119</td>
<td>15.9</td>
<td>167</td>
<td>17</td>
<td>68</td>
<td>35</td>
</tr>
<tr>
<td>28 y/o Primipara (Premenopausal)</td>
<td>30.5</td>
<td>87</td>
<td>13</td>
<td>134</td>
<td>38</td>
<td>39.2</td>
<td>32</td>
</tr>
<tr>
<td>25 y/o Para 3, SVD2, Cesarean 1, no UI (Premenopausal)</td>
<td>23</td>
<td>107</td>
<td>23.1</td>
<td>125</td>
<td>13</td>
<td>36.2</td>
<td>39</td>
</tr>
<tr>
<td>45 y/o Para2, Forceps-SVD2, GSI (Premenopausal)</td>
<td>57</td>
<td>98</td>
<td>22</td>
<td>148</td>
<td>19</td>
<td>29.6</td>
<td>38</td>
</tr>
<tr>
<td>75 y/o I7, svd7, Stage-4 prolapse, 10cm calcified fibroid, Mild GSI (post menopausal)</td>
<td>136</td>
<td>101</td>
<td>23</td>
<td>173</td>
<td>12.2</td>
<td>26.3</td>
<td>62</td>
</tr>
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</table>
these values fall within the range reported by Fielding for 10 asymptomatic subjects aged 22 – 32 years (19). But the difference may be due to normal variations in levator muscle volume, as suggested by Fielding et al. (15), or they may point to a trend of diminishing levator volume with increasing parity. The lowest volume was found in the subject with marked prolapse, who was also the patient with the highest vaginal parity. This later finding may be a result of muscle atrophy due to aging. In this group however, decreasing levator volume appears to accompany increasing vaginal parity (Table I). If this finding were substantiated in a larger study, it would suggest that vaginal delivery reduces levator volume and that significant atrophy is associated with pelvic organ prolapse.

It is also notable that the lowest volume occurred in the subject with prolapse, and the second lowest occurred in the subject with GSI, whereas the highest volume was found in the asymptomatic nullipara, and the asymptomatic parous subjects had intermediate levator volumes. These variations may also suggest a trend towards shrinking levator volumes across the range from asymptomatic subjects, through subjects with GSI, to those with pelvic organ prolapse. This echoes the question raised by Strohbehn et al. (11) about the possible relationships between pelvic muscle volume and pelvic floor dysfunction. We are currently looking at larger groups of subjects in order to define normal values for levator muscle volumes as a function of age, parity, and pelvic floor functional status.

Regarding the impact of tears in the attachment of the pubococcygeal muscle arms to the pubic rami, our small sample would suggest that such tears associated with pelvic floor dysfunction, namely GSI and prolapse. This finding needs to be substantiated in a larger study. If so, then the time delay between the occurrence of the tear [likely at childbirth (2)], and the onset of symptoms [likely at peri- or post-menopause (20-22)] would need to be explained. Is it possible that, in young premenopausal women, these tears are asymptomatic because of compensation by other factors, e.g., urethral sphincter tone, estrogen-mediated coaptation of the urethral mucosa, or intact paravaginal supports? Larger studies are needed to identify the precise relationship between pubococcygeal attachment and pelvic floor dysfunction in pre and post-menopausal women with respect to parity, and hormonal status.

The width of the levator hiatus was very similar in all except the patient with prolapse, who showed a markedly wider levator hiatus when compared to the others. This suggests a relationship between hiatus width and prolapse.

### TABLE II. PuboCoccyceal Gap (PCG) as measured on the 3D models. Longer distances may suggest a torn pubo-urethral ligament, shorter distances suggest an intact ligament; Legend in Table I.

<table>
<thead>
<tr>
<th>Patient (3D measures)</th>
<th>Left PCG (cm)</th>
<th>Right PCG (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>28 y/o Nullipara, no UI</td>
<td>1.97</td>
<td>1.77</td>
</tr>
<tr>
<td>28 y/o Primipara, no UI</td>
<td>1.95</td>
<td>1.21</td>
</tr>
<tr>
<td>25 y/o Para3, NSVD2, Cesarean 1, no incontinence</td>
<td>1.82</td>
<td>1.7</td>
</tr>
<tr>
<td>45 y/o Para2, Forceps-SVD2, GSI</td>
<td>3.17</td>
<td>1.78</td>
</tr>
<tr>
<td>75 y/o P7, sved7, Stage-IV prolapse, 10cm calcified fibroid, Mild GSI</td>
<td>2.38</td>
<td>5.42</td>
</tr>
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</table>
It is likely that the nonspecific variation in the LPA was due to the fact that MR scanning took place with the patient in the supine position, where the effect of gravity on the levators was minimized. It is possible that an upright scanning approach would better demonstrate variations in the LPA, which may be due to muscle weakness associated with prolapse or GSI, as was suggested by our earlier work (23).

Descent of the bladder neck decreased with parity. This finding was unexpected, because of the intuitive reasoning that bladder neck laxity and therefore descent accompanies increasing parity, leading to shorter bladder neck to PCL distances. However, the observed range may also represent normal variations in this parameter, and this bears further study.

The limitations of this work stem from the human and computer intensive nature of the 3D reconstruction process. Given the 12-hour processing time and specialized computing resources required for each reconstruction, we doubt the immediate feasibility of 3D reconstruction in day-to-day clinical applications. However, the ultimate goal of this research is to facilitate a better understanding of the role of the levator ani muscles in the genesis of pelvic floor dysfunction, so that we may develop better clinical markers for different types of pelvic floor dysfunction, with a view to using such markers to guide more optimal therapies. Research data suggests that estrogen replacement therapy restores elasticity to periurethral collagen tissue (24). It is possible that women with intact but weakened pubo-urethral supports could benefit from the tonic effects of estrogen replacement, or pelvic muscle reeducation, whereas those with torn supports would not benefit and would require surgical treatment. Results from larger studies may be useful in helping to develop clinical markers for identifying those women who are most likely to benefit from pelvic muscle reeducation versus estrogen therapy or surgery, thus optimizing their clinical management. Perhaps in the future, 3D pelvic floor reconstruction could also facilitate the visualization, planning and eventually, execution of pelvic floor surgeries. Specifically, interactively rendered 3D models could be useful in helping the surgeon and the trainee to identify and visualize causative anatomic defects prior to making the first incision, improving the likelihood of correcting the causative defect, and decreasing the chances of surgical failure. Such techniques have already been applied in neurosurgery (25).

REFERENCES

pelvic floor in women: quantification of muscle mass.