Open Journal of Obstetrics and Gynecology, 2022, 12, 375-385
https://www.scirp.org/journal/ojog
ISSN Online: 2160-8806
ISSN Print: 2160-8792

Review of Emerging Technologies in Pelvic Floor Ultrasonography

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How to cite this paper: De Marzi, L., Baumfeld, Y., Wei, Q. and Abbas Shobeiri, S. (2022) Review of Emerging Technologies in Pelvic Floor Ultrasonography. *Open Journal of Obstetrics and Gynecology*, **12**, 375-385.
https://doi.org/10.4236/ojog.2022.125034

Received: April 4, 2022
Accepted: May 9, 2022
Published: May 12, 2022

Abstract

Pelvic floor dysfunction is a common morbidity with a negative impact on quality of life. These disorders include multiple clinical conditions which range from urinary and defecatory disorders to sexual disorders, affecting 24% of women. Since the pelvic floor is one of the most complex regions in the human body, in order to perform an accurate diagnosis, it is important to combine history taking, physical examination and imaging. While in the past, diagnosis of pelvic floor dysfunction was done using history taking and physical examination alone, it had been recognized the need for imaging as well. In the last decades different imaging modalities have been in use, including magnetic resonance imaging and computerized tomography scanning and, nowadays, the use of ultrasonography is gaining popularity. Ultrasound technology is evolving, with technology for 3D, 4D, Doppler and more, making it optimal for pelvic floor imaging. In this paper we review the different ultrasound modalities for pelvic floor imaging. The purpose of this review is to introduce the emerging ultrasound technologies for pelvic floor imaging including volume render mode, fusion imaging, framing, motion tracking and color vector mapping and elastography. The different ultrasonography modalities have resulted to be very useful for the diagnosis and assessment of pelvic floor dysfunctions, they are characterized by availability, short time, low cost, and radiation free. However, the effectiveness of the analysis is operator-dependent.

Keywords

Pelvic Floor Ultrasonography, Volume Render Mode, Fusion Imaging, Motion Tracking, Elastography, Manometry

1. Introduction

The female pelvis is a complex of organs and tissues with different roles. It is made of the bony pelvic girdle and, different organs, including the uterus, bladder and rectum. The pelvic floor consists of muscles, ligaments and bone which hold the complex together, while allowing for different functions. These include urinating, defecating, sexual intercourse and vaginal delivery, all the while, while keeping continence. The pelvic floor can be divided according to support levels, as described by DeLancey [1], including the apical support, the lateral support to the middle part of the vagina and the pelvic floor support. It can also be divided according to three compartments which are: the anterior compartment, that is made up of the lower urinary system and the anterior portion of the vagina, the middle compartment that is made up of the uterus, cervix and apical vagina and the posterior compartment that is made up of the rectum, the anus, and the posterior portion of the vagina.

Pelvic floor disorders (PFD) are a common morbidity that includes pelvic organ prolapse, urinary incontinence and fecal incontinence. They affect between 10% - 25% of all women and have a major effect on quality of life [2]. Their prevalence increases with increasing age and weight [3] therefore, nowadays, half of women over fifty years have PFD [4].

Pelvic floor imaging is substantial for an accurate diagnosis of pelvic floor dysfunction mechanism, and assessment of the involved structures. Physical examination alone is not always enough for an accurate assessment of the disease therefore, imaging can be very useful for confirming clinical findings or to define the pelvic floor damage, leading to an optimal choice of treatment if used in adjunct to clinical evaluation.

There are several imaging modalities used for pelvic floor evaluation, including fluoroscopic defecography (FD), magnetic resonance (MR) defecography (MRD), and pelvic floor ultrasound [2] [5]. Fluoroscopic defecography is a simple and rapid examination that most closely resembles the actual process and position for physiologic defecation. Magnetic resonance defecography is a non-invasive test that can simultaneously evaluate all pelvic floor compartments and provide functional and anatomic information about muscle and ligaments with superior soft tissue contrast resolution, but it is performed only occasionally due to cost and access restrictions. As for pelvic floor ultrasound, it is an emerging modality for the investigation of functional anatomy of the pelvic floor which can provide dynamic visualization of all three compartments.

In this paper, we review some of the modern techniques of ultrasound for pelvic floor imaging, as it stands out from the other imaging methods for its access and availability, the relatively low cost and short time, and the absence of cumulative biological side effects (absence of ionizing radiation).

2. Pelvic Floor Ultrasound

Pelvic floor ultrasound is a term that encompasses a large variety of techniques:

translabial, transperineal, endovaginal, endoanal, 3D/4D acquisitions, dynamic US, assessment of vascularity patterns, and tissue stiffness-elastography [6].

Ultrasound imaging provides unique visualization of pelvic muscles and related structures using high-frequency sound waves to produce picture of the inside of the body [7]. A transducer (ultrasound probe) produces sound waves that have frequency above 20 KHz, specifically, medical ultrasound devices use sound waves in the range of 1 - 20 MHz. The choice of the right frequency is very important for providing optimal image resolution [8], furthermore, to optimize image quality, ultrasound probes may be placed inside the body.

As the ultrasound waves penetrate body tissues of different acoustic impedances along the path of transmission, some are reflected back (echo signals) to the transducer, and some continue to penetrate deeper. The echo signals return at the transducer, and they are electronically processed to increase their sizes and organized in computer memory before being displayed to the user. Thus, an ultrasound transducer works both as a speaker (generating sound waves) and a microphone (receiving sound waves) [8]. The amount of echo returned after hitting a tissue is determined by the property of the tissue (acoustic impedance). The technical development of the last 20 years (microelectronics) enables the use of more advance techniques in pelvic floor ultrasound, such as the use of multi-dimensional imaging: three dimensional (3D) (**Figure 1**) and four dimensional (4D). Such systems have been used to image the urethra, the levator ani and paravaginal supports, prolapse and implants used in pelvic floor reconstruction and anti-incontinence surgery [9].

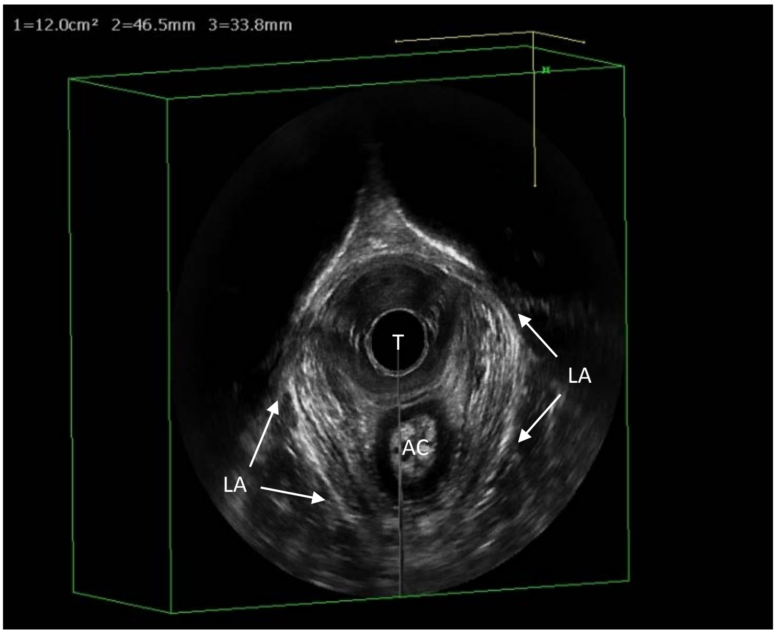

Figure 1. Three-dimensional transvaginal ultrasound image obtained with a 360˚ rotational transducer. The levator ani (LA) muscle is visualized as a multilayer structure coursing lateral to the vagina and posterior to the anal canal (AC). T: transducer.

3. Volume Render Mode

Volume rendering is a type of data visualization technique which creates a three-dimensional representation of data generated by medical imaging techniques specifically, in this case, by 3D ultrasound. The 3D data can be volume rendered to give a more complete graphical representation of the imaged anatomy. It provides greater spatial information and a more intuitive visualization of 3D anatomical structures, allowing an easier visualization of complex-shaped anatomy, as the one of the pelvic floor [10]. Furthermore, this technique gives the opportunity to obtain sagittal, axial, coronal, and any desired oblique sectional image. The 3D image can be rotated, tilted and sliced to allow the operator to visualize and measure distance, area, angle, and volume in any plane.

It uses four different post-processing display parameters: opacity, luminance, thickness, and filter; so that it can provide a better visualization when there aren't any large differences between the signal level from pathologic structures and the surrounding tissues. For example, it seems to be a very promising method for detailed evaluation of the integrity or injuries of the pelvic floor muscles, and for the assessment of the location of mesh after pelvic floor reconstruction surgery.

This technique is very useful for detecting abnormalities in the morphology and structure of pelvic floor. In the study of Ying *et al.* [11] volume rendering has been used to study the pelvic floor of 50 nulliparous and 50 pelvic organ prolapse women. The size and the position of the levator hiatus, puborectalis and pelvic organs were observed and compared between both groups, by taking three evaluating metrics as reference: levator hiatus area, anteroposterior diameter of the levator hiatus, and left-to-right diameter of the levator hiatus. The levator hiatus of POP women turns out to have a bigger size, a more circular morphology, and its axis departs from the pelvic floor axis, whereas in nulliparous women the two axes overlapped. The puborectalis was avulsed, and the pelvic organs arranged abnormally [11] [12].

4. Fusion Imaging

Fusion imaging is a technique that fuses two different imaging modalities. Real-time ultrasonography (US) is usually fused with other imaging techniques such as computerized tomography (CT), magnetic resonance (MR), and positron emission tomography (PET). Because of this fusion, the CT or MR or PET images show the same plane and move synchronously while performing real-time US [13] [14]. This modality enables to compensate the deficiencies of one method and retain the advantages of another one; it allows the direct comparison of the lesions, more precise monitoring of interventional procedure and increase diagnostic confidence [15].

For example, in the article of Egorov *et al.* [16], the researchers have explored the imaging performance and clinical value of vaginal tactile and ultra-sound image fusion, enabling the biomechanical characterization of the female pelvic floor. Tactile Imaging translate the sense of touch into a digital image: it translates muscle activity into dynamic pressure pattern. This technique, called Vaginal Tactile Imager (VTI), provides a biomechanical mapping of the female pelvic floor to quantify tissue elasticity, pelvic support, and pelvic muscle functions. It allows a high-resolution mapping of pressures and assesses the strength of pelvic floor muscle (PFM) within the vagina to assist in diagnosis [17]. However, VTI does not allow biomechanical mapping of the female pelvic floor structures with accurate anatomical identification. To overcome the VTI's limitations the researchers combined ultrasound imaging and tactile imaging, providing tissue stress data with the tactile sensor arrays, as well as combining the anatomical and tissue strain data with the ultrasound transducers. After studying twenty women with this method, they provided unique data for biomechanical characterization of the female pelvic floor. The technique allowed recognition and characterization of the levator ani muscles, perineum, urethral and anorectal complexes, which are critical in prolapse and/or incontinence development [16].

5. Framing

Framing is a modality that provides a detailed visualization of the motion sequences of specific structures. The framing technique enables analyzing consecutive frames of a video file [18] and allows capturing the motion of the pelvic structures [19].

6. Motion Tracking and Color Vector Mapping

Motion tracking is a modality for the assessment of biomechanical properties of tissues and organs, it can help to understand the complex functional interactions among pelvic organs, muscles, ligaments, and connective tissue. This technique provides quantitative measures such as displacement, velocity, acceleration, motility, trajectory, and strain of pelvic floor muscles and, for example, it allows the distinction between women with and without stress urinary incontinence.

This technique has been used in the article of Peng *et al.* [20] to analyze the dynamic parameters of pelvic floor muscle on the ano-rectal angle (ARA), of twenty-two asymptomatic females and nine with stress urinary incontinence. To map accurately the trajectory of the ARA, every frame was indexed to the same rigid landmark, the symphysis pubis (PS) which is a stationary, rigid, nondeforming structure. Through some algorithm they tracked the motion of ARA and PS, and the relative movement of ARA to the SP was then derived by subtracting the motion of SP from that of ARA. This study showed that the pelvic floor muscles function differently in continent women and in those with stress urinary incontinence, the PFM provides an active role to the continence mechanism by providing active support at the appropriate time to the urogenital structures. With this technique the researchers were able to provide significant new information relating to the dynamic response to stress of the pelvic floor.

Furthermore, motion tracking has been used for evaluating the PFM dynamics activity of stress incontinent women pre- and post- operatively and asymptomatic subjects [19].

For the visualization of the movement there are different techniques: color-based visualization according to length values of displacement vectors, vector-based visualization, in which arrows represent the length and spatial orientation of moving matter, and line-paths-based visualization where the path of the motion of a small set of points is visualized. A variation of the third technique allows the visualization of the path length values of a whole region [18]. These techniques can be very useful for the diagnosis of injuries or deficiency of pelvic muscles and for the evaluation of muscle strength.

7. Elastography

Elastography uses ultrasonic imaging to observe tissue shear deformation after applying a force that is either dynamic or varying so slowly that is considered "quasi-satic" [18]. The strain measurements are displayed as a semitransparent color map called an elastogram, which is overlaid on the B-mode image (**Figure 2**). This technique allows quantification of the elasticity and stiffness of tissues, and it can be useful for the assessment of pelvic floor biomechanics. Muscle stiffness can be used as an estimate of muscle force, for example, elastography has been used for evaluation of the levator ani in patients with pelvic organ prolapse (POP) stage I/II before and after Kegel exercises. It has also been used for the assessment of levator avulsion injury in postpartum pelvic floor trauma and, to distinguish malignant from benign tumors [18].

Several studies have used this technique for assessing the elastic profile of pelvic floor muscle in women with stress urinary incontinence [21] [22] [23]. One study explored [22] the transperineal elastography to investigate the elasticity of the levator ani muscle of patients suffering from stress urinary incontinence. After locating the LAM by conventional transperineal ultrasound, they performed the elastography assessment. Light pressure was applied, and the variable color/coded strain appeared in the elastogram, different colors indicated different tissue stiffness. With this study they demonstrated that the improvement of stress urinary incontinence was associated with the stiffer LAM evaluated by elastography, women with urinary incontinence who have softer LAM were more likely to have symptoms of SUI.

The article of Abe-Takahashi *et al.* [24] is another example of implementation of the elastography technique. Here, real-time tissue elastography has been used to compare pelvic floor muscle elasticity between interstitial cystitis/bladder pain syndrome (IC/BPS) patients and healthy women. They located the striated urethral sphincter (SUS) by transperineal ultrasound and, immediately after, the transperineal elastography was carried out, therefore gray-scale ultrasound and elastography images were shown simultaneously. Through this technique they showed that SUS strain ratio at rest was significantly higher, which indicates lower elasticity, in IC/BPS patients than in healthy young adult and middle-aged women.

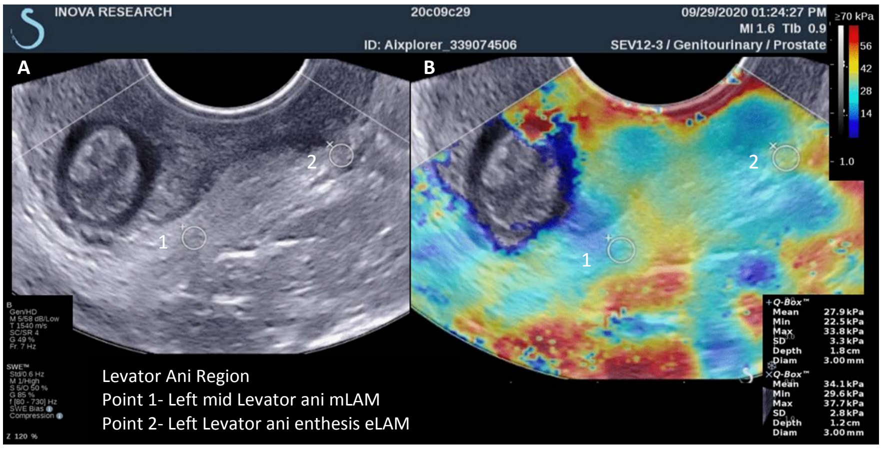

Figure 2. (A) Conventional ultrasound and (B) elastography of the levator ani region. Depth and elastography moduli from 2 measurement sites are displayed on the right side.

8. Manometry

Pelvic floor manometry consists of the measurement of resting pressure or pressure rise generated during contraction of the PFM through a manometer, which is a device for measuring pressure, connected to a sensor inserted into the urethra, vagina or rectum [25] [26]. The pressure measurements are displayed as a color map in which the higher pressure is represented by red color and the lower pressure by blue color (**Figure 3**). This technique is very useful for the assessment of pelvic floor muscle function in both women and men [27] [28]. Furthermore, it has been implemented for the comparison of pelvic floor muscle strength between women undergoing vaginal delivery, cesarean section, and nulliparae [29]. In the article of Alshiek *et al.* [30], it has been used to study the effects of aging on the 3D vaginal manometry parameters, and the correlation between changes in these parameters and sexual function, prolapse and urinary status. Furthermore, in the article of Raizada *et al.* [31], the researchers have combined high-definition manometry (HDM) with 2D ultrasound imaging to better study the pelvic floor muscles. Specifically, HDM has been used to identify the vaginal high-pressure zone (HPZ) and study its static and dynamic characteristic, then, 2D ultrasound imaging of the pelvic floor muscles has been implemented to further understand the characteristics of vaginal HPZ.

9. Discussion

As it emerged in the previous paragraphs, in the last decade, the ultrasound imaging technology has improved dramatically, allowing for clearer and more defined images and, therefore, a better understanding of the pelvic floor region.

The ultrasonography technologies have their own disadvantages, first among all, the strong operator-dependance. The quality of results and the use of the equipment of each one of the emerging ultrasound variations and modalities that I've described in this review, depend on the operator's skill. Furthermore, the images can be more difficult to interpret, compare, for example, to magnetic

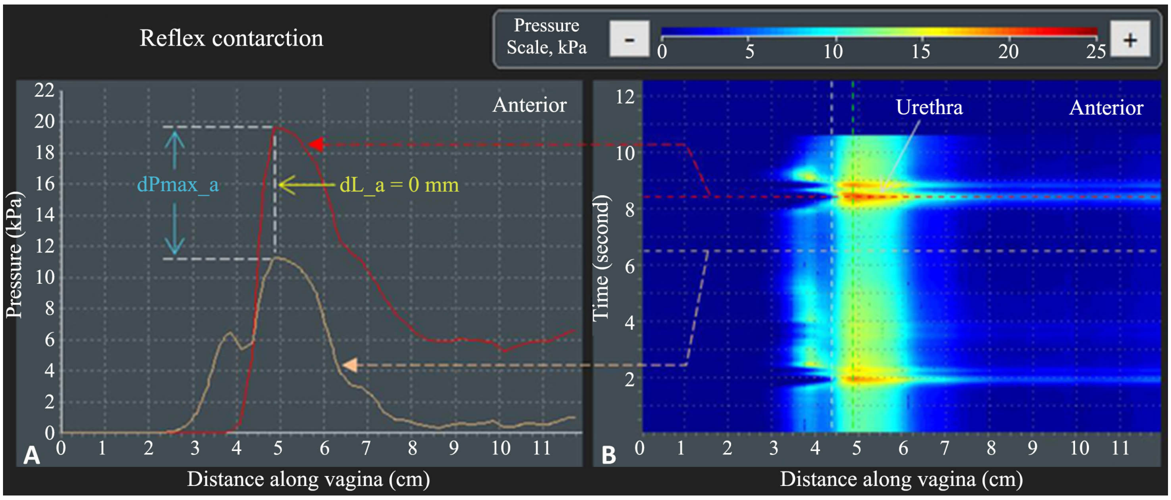

Figure 3. Pressure graphic and manometry. (A) Anterior pressure patterns at muscle contraction (red lines) and at rest (light brown lines); (B) Anterior dynamic pressure pattern along the vagina.

resonance, which has a greater resolution. Therefore, ultrasound technologies required improved anatomical knowledge and experienced operators. However, there are a lot of advantages that make ultrasound one of the best modalities for the analysis of the pelvic floor. Volumetric ultrasound can create images with more depth and details, closely replicating the region analyzed, Elastography can provide mechanical properties of tissues, Fusion Imaging can overcome some of the complications previously mentioned by combining ultrasound with another technologies, Manometry is very useful for the assessment of the pelvic floor muscle function, Framing makes easier the analysis of the ultrasound video file and Motion Tracking is very useful for the biomechanical assessment of the region and to understand how the different muscles and organs interact with each other. Each one of the technologies that I've presented has its own advantages and it's best used in specific situation, but each one shares the wide availability, the relatively low cost and portability, the possible real-time and, except for the fusion imaging method, the absence of ionizing radiation, which can damage biological materials.

10. Conclusion

The women's pelvic floor is one of the most complex regions of human body and the correct diagnosis of specific pelvic floor disorders is not an easy task. Different imaging techniques have been implemented to complement clinical evaluation. Ultrasound imaging has resulted in an extremely valid approach for the analysis of the pelvic floor region, mainly because, in the last decades, there have been several ultrasound technical innovations that allowed an improvement and a more advanced diagnosis of pelvic floor dysfunction. 3D and 4D ultrasound imaging, volume render mode, fusion imaging, framing, motion tracking and color vector mapping, elastography, and other modalities which were not introduced in this review, enable an in-depth analysis of the organs, the muscles and the connective tissues that constitute the complex region of the pelvic floor.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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