Ultrasound imaging of the pelvic floor.
Part II: three-dimensional or volume imaging

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ABSTRACT
In this second part of a review of pelvic floor ultrasound imaging, current three-dimensional (3D) ultrasound technology and its use for imaging pelvic floor structure and function is described. Recent technical developments enable rapid automated volume acquisition in real time, and currently available transducers designed for abdominal use are well suited for translabial/transperineal imaging. To date, 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. While 3D pelvic floor imaging is a field that is still in its infancy, it is already clear that the method has opened up entirely new opportunities for the observation of functional anatomy. Copyright © 2004 ISUOG. Published by John Wiley & Sons, Ltd.

INTRODUCTION AND TECHNICAL OVERVIEW
Ever since the advent of B-mode ultrasound imaging the main purpose of diagnostic ultrasound has been the acquisition of sectional planes. It is not surprising, therefore, that the first attempts at producing three-dimensional (3D) capable systems go back to the 1970s when the processing of a single volume of data would have required 24 h of computer time on a system large enough to fill a small room. Due to the phenomenal development of microelectronics, such data processing can now be done on a laptop, and in real time.

Acquisition of volumes
Two main engineering solutions were developed to allow integration of two-dimensional (2D) sectional images into 3D volume data: motorized acquisition and external electromagnetic position sensors. The latter is commercially available, but there are no publications documenting its use in pelvic floor imaging. A simplified technique is the freehand acquisition of volumes without any reference to transducer position. In essence, this means that a cineloop of images is integrated into a volume; as the system has no information on transducer position relative to the insonated tissues, measurements on volume data are impossible. Nevertheless, qualitative information may be obtained, and such systems have been used for clinical research in urogynecology.

However, quantitative evaluation of volumes requires information on transducer position at the time of acquisition of a given frame of imaging data. This is most conveniently achieved by using a motor, the characteristics of which will determine imaging data coordinates. Motorized acquisition may take the form of automatic withdrawal of an endocavitary probe or motor action within the transducer itself. The first such motorized probe was developed in 1974, and by 1987 transducers for clinical use were developed that allowed motorized acquisition of imaging data. The first commercially available system platform, the Kretz Voluson, was developed around such a ‘fan scan’ probe since the company’s strong base in gynecology made endocavitary applications of prime interest. Endocavitary probes make a freehand acquisition technique highly impractical which is why the company did not develop this alternative approach further and instead concentrated on a technology reminiscent of mechanical sector transducers. The result has been the abdominal and endovaginal probes used in systems such as the GE Kretz Voluson 730 series, the Philips HDI 4000 and the Medison SA 8000–9900 series of systems, and competitors such as Siemens and Aloka are now marketing similar technology. The widespread acceptance of 3D ultrasound in obstetrics and gynecology was aided considerably by the development of these systems since they do not require...
any movement relative to the investigated tissue during acquisition.

Automatic image acquisition is achieved by rapid oscillation of a group of elements within the transducer head, allowing the acquisition of not just one but a multitude of sectional planes. These can be integrated into a volume since the location of a given pixel (or, to use the correct term for a pixel that has a defined location in space, a ‘voxel’) within the volume of investigated tissue is fully described by transducer and insonation characteristics. At present this approach can be regarded as the most advanced technology available. In the future, multiple arrays of elements in a fixed arrangement may provide even faster acquisition speeds\(^1\), and it appears that such systems are already in use in cardiology imaging\(^4\).

Fortuitously, transducer characteristics on currently available systems for use in obstetrics and gynecology have been almost perfect for pelvic floor imaging. They are well suited to translabial or perineal scanning, with the transducer placed on the introital area in a midsagittal orientation. A single volume obtained at rest with an acquisition angle of 70° or higher will include the entire levator hiatus with symphysis pubis, urethra, paravaginal tissues, the vagina, anorectum and puborectalis loop from the pelvic sidewall in the area of the arcus tendineus of the levator ani (ATLA) to the posterior aspect of the anorectal junction (Figure 1). Depending on the anteroposterior dimensions of the puborectalis loop, it may also include the anal canal and even the external sphincter. Of course this also holds true for volumes acquired on levator contraction since this shortens the levator hiatus in the anteroposterior direction without altering its lateral dimensions significantly. A Valsalva maneuver, however, may result in lateral or posterior parts of the puborectalis being displaced outside the field of vision, especially in women with significant prolapse (see below).

Display modes

Figure 1 demonstrates the two basic display modes currently in use on 3D ultrasound systems. The multiplanar or orthogonal display mode shows cross-sectional planes through the volume in question. For pelvic floor imaging, this most conveniently means the midsagittal (Figure 1a), the coronal (Figure 1b) and the axial (Figure 1c) planes.

One of the main advantages of volume ultrasound for pelvic floor imaging is that the method gives access to

![Figure 1](https://example.com/figure1.png)

**Figure 1** The usual acquisition/evaluation screen on Voluson-type systems shows the three orthogonal planes: (a) sagittal, (b) coronal and (c) axial, as well as (d) a rendered volume, which is a semitransparent representation of all gray-scale data in the rendered volume (box delineated in (a), (b) and (c)).
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The axial plane on (a) magnetic resonance imaging and (b) ultrasound (freehand three-dimensional). While these images were obtained in different patients, all significant structures can be identified by both methods. Image (a) courtesy of Dr Ben Adekamnu, Plymouth, UK.

Figure 2

The possibilities for postprocessing are restricted only by the software used for this purpose; programs such as GE Kretz 4D View (GE Kretztechnik GmbH, Zipf, Austria) or Philips Sonoview Pro (Philips Australia, North Ryde, Australia) allow almost unlimited manipulation of image characteristics.

4D imaging

Four-dimensional (4D) imaging implies the real-time acquisition of volume ultrasound data, which can then be represented in orthogonal planes or rendered volumes. Most recently, it has become possible to save cineloops of volumes, which is of major importance in pelvic floor imaging. Even on 2D single-plane imaging, a static assessment at rest gives little information compared with the evaluation of maneuvers such as a levator contraction and Valsalva. The observation of such maneuvers will allow an assessment of levator function and delineate levator or fascial trauma more clearly. Avulsion of the puborectalis–pubococcygeus complex from the ATLA may only become evident on Valsalva, and most significant pelvic organ prolapse is not visible at rest in the supine position. Fascial defects such as those defining a true rectocele (see
The ability to perform a real-time 3D (or 4D) assessment of pelvic floor structures makes the technology potentially superior even to MRI. Prolapse assessment by MRI requires ultrafast acquisition, which is of limited availability and will not allow optimal resolutions. Alternatively, some systems allow imaging of the sitting or erect patient, but again accessibility will be limited for the foreseeable future. The sheer physical characteristics of MRI systems make it much harder for the operator to ensure efficient maneuvers as more than 50% of all women will not perform a proper pelvic floor contraction when asked, and a Valsalva maneuver is often confounded by concomitant levator activation (see Part I of this review). Without real-time imaging these confounders are impossible to control for. Therefore, ultrasound has major potential advantages when it comes to describing prolapse, especially when associated with fascial or muscular defects, and in terms of defining functional anatomy.

Consequently, a truly functional anatomical assessment is at present only feasible with 3D volume ultrasound. This encompasses the observation of downwards displacement of pelvic organs on Valsalva, the development of prolapse, the opening up of fascial or muscular defects, and the effect of a contraction and Valsalva on the levator hiatus. Figure 3 shows frames representing the levator hiatus at rest and on maximal Valsalva in a nulliparous young woman with minimal pelvic organ descent; in an individual with prolapse the levator hiatus often increases markedly in size, even without actual defects (Figure 4).

In effect it is now possible to acquire a cineloop of 64 volumes which, if timed properly, could contain both a levator contraction and a maximal Valsalva, therefore allowing a complete assessment of functional pelvic floor anatomy on one single dataset of approximately 150 MB. Handling and storage requires up-to-date processing capabilities and adequate hard disk space. Such quantities of data will tax even the most modern network, and a DVD burner or an external hard disk are indispensable for portability. Once volumes are stored, however, the result for the clinician is akin to having the patient available for re-examination at any time.

### Practical considerations

One of the criticisms that have been leveled at pelvic floor ultrasound is that it is highly operator-dependent, which is true as for all real-time ultrasound. 3D systems will reduce this operator dependence since volume acquisition is easily taught and should be within the capabilities of every sonographer or sonologist after a few days’ teaching. While the method does require postprocessing (and the skills involved in this are more significant), static volume
data typically of 2–6 MB in size can be de-identified and transmitted electronically so that evaluation may be obtained by e-mail, and this opens up entirely new possibilities for local and international cooperation. In the future, acquisition of pelvic floor imaging data via 3D and 4D volume ultrasound may well become an integral part of any urogynecological work-up, just as multichannel urodynamics is today. Until recently, data formats were compatible between the three leading manufacturers. This compatibility is about to be lost, however, and companies involved in 3D imaging should be strongly urged to establish industry-wide volume data formats to simplify data exchange and analysis.

LITERATURE REVIEW

Currently, most publications on 3D ultrasound in obstetrics and gynecology deal with obstetric applications. The visualization of fetal structures such as extremities and face is what has, to a large extent, driven research and development as well as the marketing of these systems. While fascinating and helpful images may be obtained this way, and while well-selected 3D data may enhance the understanding of certain conditions or abnormalities for both patients and caregivers, some critics may contend that 3D ultrasound has been a technology searching for an application. Pelvic floor imaging is a minor niche within the field of ultrasound in obstetrics and gynecology, but it may provide one of the first true indications for 3D volume ultrasound imaging.

In the following paragraphs a review of research on pelvic floor 3D ultrasound will be attempted. Most of the published material does not make full use of the capabilities of this technology as outlined above. Recent progress has been rapid in this field, and it is to be expected that it will take several years for this progress to be reflected in the published literature, let alone the textbooks.

To date, 3D pelvic floor ultrasound has been used for the evaluation of the urethra and its structures, for imaging of the more inferior aspects of the levator ani complex (pubococcygeus and puborectalis), for the visualization of paravaginal supports, and for prolapse and implant imaging.

3D imaging of the urethra

Technically, 3D pelvic floor ultrasound imaging became feasible in 1989–1990 with the advent of the Kretz Voluson 530 systems. However, there are no records of any such use of those first true clinical 3D ultrasound systems; the first publication on 3D ultrasound in urogynecology dates back to 1994 when Linda Cardozo’s group at King’s College London, demonstrated that this technique could be used to assess the urethra. Khullar et al. used transvaginal probes to allow the use of calipers in all three planes. Subsequently, it was shown that urethral volumetry data correlated with urethral pressure profilometry, and that urethral volume decreased with parity. More recently, this technique has been used to assess delivery-related changes, and 3D ultrasound with intravaginal systems may aid in identifying paraurethral support structures such as the pubourethral ligaments. Probes designed for prostatic imaging have also been employed for the assessment of the urethra and paraurethral structures by the transrectal route.

3D imaging of the levator ani complex

To date, the levator ani has not been comprehensively investigated by 3D volume ultrasound. While it was identified on early studies using transvaginal techniques and translabial freehand volume acquisition as well as on translabial ultrasound using a Voluson system, the focus of these reports was on the urethra and paraurethral tissues. With translabial acquisition the whole levator hiatus and surrounding muscle (pubococcygeus and puborectalis) can be visualized as a highly echogenic structure. Similar to MRI, it is currently impossible to distinguish the different components of the pubovisceral or puborectalis–pubococcygeus complex. Observation of the muscle during levator contraction and on Valsalva may increase the likelihood of detecting abnormalities of levator morphology. In a series of 52 young, nulligravid women published recently, no significant asymmetry of the levator was observed, supporting the hypothesis that marked morphological abnormalities of the levator are likely to be evidence of delivery-related trauma. Contrary to MRI data, there was no significant side difference, neither for thickness nor for area.

The above-quoted 3D ultrasound study defined a number of biometric parameters of the levator complex itself and of the levator hiatus. Results agreed with MRI data obtained in small numbers of nulliparous women for the dimensions of the levator hiatus and levator thickness. In a test–retest series it became evident that, with current methodology, diameter and area measurements of the pubococcygeus–puborectalis complex are less reproducible than measures of the levator hiatus. Possibly as a consequence, measures of muscle mass did not correlate with levator function as determined by displacement of the bladder neck on levator contraction, a finding that agrees with clinical impressions: a bulky levator may not necessarily contract well.

Hiatal depth and area measurements (Figures 3 and 4), however, were highly reproducible (intraclass correlation coefficients of 0.70–0.82) and correlated strongly with pelvic organ descent, both at rest and on Valsalva. While this is not surprising for the correlation between hiatal area on Valsalva and descent (as downwards displacement of organs may push the levator laterally), it is much more interesting that hiatal area at rest is associated with pelvic organ descent on Valsalva. These data constitute the first hard evidence for the hypothesis that the state of the levator ani is important for pelvic organ support, even in the absence of levator trauma. Further work will have to focus on the observation of levator anatomy and function before and after childbirth (to determine the etiology of, and risk factors for, morphological
Figure 5 Levator avulsion (lower arrows) on (a) magnetic resonance imaging (MRI) and (b) three-dimensional ultrasound. While these images were obtained in different patients, the appearances are typical in that a levator avulsion seems to most often occur on the patient’s right (left side of the images). In both cases paravaginal tenting is also absent on the patient’s right (top arrows). MRI image courtesy of Dr Ben Adekamni, Plymouth, UK.

Figure 6 Loss of tenting postpartum (arrow) in a primipara after term normal vaginal delivery. (a) Antepartum rendered volume and (b) postpartum volume (freehand technique).
abnormalities) and on cross-sectional studies of levator anatomy in asymptomatic and symptomatic older women to determine whether such abnormalities are associated with clinical symptoms, conditions or surgical outcome. From experience to date, it is evident that major levator trauma, i.e. avulsion of the puborectalis–pubococcygeus from the pelvic sidewall, is not that uncommon (3–5% in symptomatic women) and seems to be associated with early presentation and recurrent prolapse after surgical repair (Figure 5).

3D imaging of paravaginal supports

It has long been speculated that anterior vaginal wall prolapse and stress urinary incontinence are at least partly due to disruption of paravaginal and/or paraurethral support structures, i.e. the endopelvic fascia and pubourethral ligaments, at the time of vaginal delivery. However, proof has been lacking to date. In a pilot study in a group of women before and after their first delivery, the author attempted to define the integrity of paravaginal supports (‘tenting’, see Figure 6), using a Toshiba PowerVision 8000 system (Toshiba Medical Systems) with freehand acquisition technique. While this technique is now already obsolete, it still yielded interesting results. Alterations in paravaginal supports were observed in 5/21 women seen both ante- and postpartum, and interobserver variability of the qualitative assessment of paravaginal supports was shown to be good. An incidental observation was that imaging quality was exceptional in late pregnancy, probably due to increased hydration of tissues.

Somewhat counterintuitively there was no significant correlation between a loss of paravaginal support and increased bladder neck or urethral mobility on Valsalva in this study. The authors speculated that increased mobility might not necessarily mean disruption or avulsion of structures but rather stretching or distension, but it was pointed out that the method might not be powerful enough to detect changes due to the limitations of a freehand technique. Another weakness of this study was that Valsalva volumes were obtained but not evaluated due to difficulties with orientation, and the levator ani was not assessed either. The author is currently involved in a continuation of this work, using systems with automatic image acquisition, which should avoid the more obvious shortcomings of the above-quoted study. Paravaginal tissues can also be assessed by transrectal or transvaginal 3D imaging.

Figure 7 Large cystocele in the three standard planes: (a) sagittal, (b) coronal and (c) axial, plus (d) a rendered image (axial, caudocranial rendering) showing a view through the cystocele onto the bladder roof.
ultrasound using probes designed for pelvic or prostatic imaging\textsuperscript{24}, but this work does not seem to have progressed beyond the preliminary stage.

It remains to be shown whether loss of paravaginal tenting is in fact equivalent to what is clinically described as a ‘paravaginal defect’, a concept that is controversial even in clinical urogynecology\textsuperscript{29,30}. In a recent study on 62 women presenting with pelvic floor disorders, only weak correlations were found between a blinded clinical assessment for paravaginal defects and the presence or absence of tenting in single planes or rendered volumes obtained by 3D translabial ultrasound (automatic image acquisition), and even this weak correlation was only seen on Valsalva\textsuperscript{31}. This may be due to inadequate clinical assessment technique or possibly an insufficiently sensitive imaging method. However, another explanation may be that true paravaginal defects are either not common or irrelevant for anterior vaginal wall support (or both). Until credible data are presented that demonstrate the reproducible detection of paravaginal defects preoperatively and validate this against the reproducible, blinded detection intraoperatively, the paravaginal defect as such has to be regarded as an unproven concept\textsuperscript{31}.

3D imaging of prolapse

The downwards displacement of pelvic organs on Valsalva maneuver in itself does not require 3D imaging technology, whether MRI- or ultrasound-based. Descent of the urethra, bladder, cervix, cul de sac and rectum is easily documented in the midsagittal plane\textsuperscript{32}, and the technology required for this purpose has been available for more than 20 years (see Part I of this review\textsuperscript{19}). However, 3D ultrasound is likely to become useful in the location of fascial defects (e.g. transverse or lateral tears of the rectovaginal septum). Rendered volumes may allow complete 3D visualization of a cystocele or rectocele (Figures 7 and 8). When processed into rotational volumes, hyperechogenic structures such as a stool-filled rectocele become particularly evident. The ease with which pre- and postoperative data can be compared with the help of stored imaging volumes will be especially useful in audit activities.

3D imaging of synthetic implant materials

The imaging of synthetic implants may yet prove to be a major factor in the uptake of this new investigational

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Figure 8 Large rectocele in the three standard planes (a) sagittal, (b) coronal and (c) axial, plus (d) a rendered volume showing a large symmetrical rectocele filling most of the levator hiatus (arrow).
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... technique into clinical practice. Suburethral slings such as the TVT (tension-free vaginal tape, Johnson & Johnson Medical, North Ryde, Australia), SPARC (Suprapubic Arc Tape, American Medical Systems, North Parramatta, Australia) or IVS (Intravaginal Slingplasty, Tyco Healthcare, Lane Cove, Australia) have become very popular during the last 10 years and are now the primary anti-incontinence procedure in many developed countries. These slings are not without their problems, even if biocompatibility is markedly better than for previously used synthetic slings. Imaging of such slings may be indicated in research, in order to determine the location and function of such slings, and possibly even for assessing in vivo biomechanical characteristics. Clinically, complications such as sling failure, voiding dysfunction, erosion and symptoms of the irritable bladder may benefit from imaging assessment.

Fortunately, most of the modern synthetic implant materials are highly echogenic (see Part I of this review), with TVT and SPARC usually being more visible than the IVS. 3D ultrasound has been used to locate the implant over its whole course, from above the pubic rami to behind the urethra, and back up on the contralateral side (Figure 9). Variations in placement such as asymmetry, varying width, the effect of tape division and tape twisting can be visualized. The difference between transobturator tapes and TVT-type implants, impossible to distinguish on 2D imaging, is readily apparent on rendered volumes (Figure 10). It is quite likely, therefore, that 3D imaging will become helpful in the assessment of suburethral slings.

The same holds true for mesh implants used in prolapse surgery. There is a worldwide trend towards mesh implantation, especially for recurrent prolapse, and complications such as failure and mesh erosion are not uncommon. While there are no publications on the imaging of mesh by 3D ultrasound at present, the new method will be useful in determining functional outcome and location of such implants (Figure 11). Finally, most of the injectables used in anti-incontinence surgery are also highly echogenic and can be visualized surrounding the urethra (Figure 12).

CONCLUSIONS

3D volume ultrasound adds not one, but several, dimensions to pelvic floor imaging, in particular in its most

Figure 9 The tension-free vaginal tape (TVT) as imaged on an oblique rendered volume of the levator hiatus. The mesh structure of the tape is clearly visible. There is also a local abnormality of the levator on the patient’s right (left side of the image, indicated by the arrow).

Figure 10 (a) Monarc sling vs. (b) tension-free vaginal tape (TVT) sling in rendered volumes of the levator hiatus. The difference in placement is obvious: the Monarc sling is inserted through the obturator foramen, the TVT through the space of Retzius. As a result the latter is situated much more medially.
recent incarnations using automatic volume acquisition and cine volumes. The technology opens up entirely new possibilities for observing functional anatomy and examining muscular and fascial structures of the pelvic floor. Data acquisition will be simplified and research capabilities enhanced, and surgical audit in this field will undergo significant change. It will be many years before the potential for true progress inherent in this new technology is fully realized.

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