Levator ani muscle during pregnancy and delivery outcome:

A three- and four-dimensional transperineal ultrasound study

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"Wenn ich wüßte, daß morgen die Welt untergeht,
würde ich heute noch ein Apfelbäumchen pflanzen."

attributed to Martin Luther

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1 Introduction

"The hominid birth canal became very like the present human one; a deep curved tube rather than a straight shallow ring, enclosed at its lower end by soft tissues which are adapted for holding things in rather than for letting them out". From: The pelvis is a passageway. By D.B. Stewart [(1)]

The evolutionary process of upright walking (bipedalism) started approximately 4-5 million years ago and changed the shape of the human bony pelvis [(2)] and involved a considerable remodelling of the muscles and fasciae of the pelvic floor [(1)]. In quadrupeds, the weight of the abdominal contents is distributed along the vertebral canal and carried by the abdominal wall, whereas in humans half of the body weight and the growing uterus with the developing fetus must be supported by the pelvic bones and the pelvic floor soft tissues [(3)]. The process of bipedalism resulted in a rather constricted birth canal [(1, 3)]. It is assumed that 600,000-150,000 years ago, rapid and major increase in the fetal brain size (encephalization) evolved [(2, 4)]. This placed competing demands on the human pelvis and on the human pelvic floor: the increasingly large-headed neonates had to be delivered through a pelvis that had earlier been adapted to bipedalism [(2, 5)].

The levator ani muscle is the largest of all the pelvic floor muscles. Its medial part forms a u-shaped sling around the urethra, the vagina and the rectum, thereby bordering the levator hiatus, the largest potential hernia portal in the human body [(6, 7)]. Its anatomy and function are a compromise between conflicting priorities [(6)]. The main purpose of the levator ani muscle is to keep the levator hiatus closed, thereby contributing to maintaining continence and pelvic organ support [(8, 9)]. This requires limited dimensions of the levator hiatus [(8-10)]. On the other hand the levator ani muscle has to distend considerably during childbirth [(10, 11)] to facilitate the passage of the fetus. Thereby a limited size of the levator hiatus and limited ability to distend during delivery might prolong the second stage of labour and thus necessitate instrumental intervention during childbirth [12, 13]. Complicated deliveries can cause adverse outcomes for both mother and child. Complicated deliveries are associated with an increased risk of infant morbidity and mortality and maternal psychological trauma, postpartum haemorrhage, infection and injuries to different structures of the pelvic floor [14, 15]. The women's satisfaction with the birth process and quality of life postpartum are of growing importance in modern obstetric care [16]. Thus, if the levator hiatus dimensions during pregnancy are associated with long and traumatic deliveries, information regarding these dimensions before delivery would be of use for both the women and the clinician in order to improve informed consent and decision-making regarding the process of labour [16, 17].

The large distension of the levator ani muscle might lead to tearing of parts of the muscle from its bony insertion, so-called "major levator ani muscle defects" [11, 18, 19]. Childbirth-related injuries of the pelvic floor, especially major levator ani muscle defects, have been identified as important factors in the pathogenesis of pelvic floor dysfunction [20-23]. These debilitating conditions affect the quality of life of many women and have an important impact on the healthcare system and costs [24-26]. In order to develop preventive strategies for pelvic floor dysfunction, there is a need for more detailed understanding of childbirth-related injuries to the pelvic floor [21, 27]. At the time this research project was planned, there was scant knowledge of the association between levator hiatus dimensions and the functional aspects of the levator ani muscle during pregnancy and the occurrence of major levator ani muscle defects during parturition [28].

One reason for the lack of knowledge on the impact of antenatal levator hiatus dimensions on the process of delivery and major levator ani muscle defects [12, 13, 28] is that the muscle has not been easy to assess as it lies hidden from surface anatomy. It is only in recent years that safe and convenient assessment of the levator hiatus and the functional aspects of the levator ani muscle have been possible by using three- and four-dimensional transperineal ultrasound [29, 30].

When a new diagnostic tool is introduced, it is important to ensure the reliability of the measurements used [31]. Several studies have shown high intra- and inter-rater reliability for measurements of levator hiatus dimensions [29, 30, 32-35]. However, the reliability-data refers only to the process of offline analysis as the levator hiatus measurements were made on stored datasets previously acquired by only one investigator [29, 30, 32-35]. Thus, the source of variability in the measurements resulting from to the process of volume acquisition itself was not taken into account [36]. For a new tool to be accepted into clinical practice, it is also important that the length of the learning process for the procedure is not too long. As far as we have ascertained, no learning study for the process of volume acquisition and offline analysis of levator hiatus dimensions using three- and four-dimensional transperineal ultrasound was published when the present research project was planned.

The overall aim of this thesis was to evaluate the learning process of volume acquisition and offline analysis of three- and four-dimensional ultrasound data of the levator hiatus, as well as performing an interobserver reliability study for the entire procedure, both volume acquisition and offline analysis, for two investigators. Furthermore, we aimed to assess the association between antenatal levator hiatus dimensions for both the process of labour and major levator ani muscle defects using three- and four-dimensional transperineal ultrasound.

2 Background

2.1 Pelvic floor

The term pelvic floor is not consistently defined in literature. Some authors define the pelvic floor as the tissues that fill the cavity of the pelvic canal: all muscles, connective tissue and the viscera (37): the bladder and the urethra, the vagina and the uterus and the rectum (38, 39). Other authors do not include the viscera in their definition of the pelvic floor (40-42). The soft tissues are all enclosed within the framework of the bony pelvis, which forms a scaffold from which the muscle and organs are suspended (38).

2.1.1 Anatomy

Bony pelvis

The bony pelvis consists of the ilium, ischium, pubis, sacrum and coccyx. They are connected by three principal joints: the symphysis pubis and two sacroiliac joints (38). It is further held in place by several ligaments including the sacrospinous, sacrotuberous, sacrococygeal and sacroiliac ligaments (38, 43).

Supportive connective tissue

The endopelvic fascia lies beneath the peritoneum, surrounding the vagina and part of the uterine cervix and attaches these organs to the pelvic sidewalls (8, 38, 44), yet allowing their displacements and changes in volume (44). It is a mesh-like group of collagen fibres interlaced with nerves, lymph vessels and smooth muscles fibres (44, 45). This connective tissue network has various thickenings and condensations in specific areas [44]: the arcus tendineus fasciae pelvis (fascial white line) [9, 45, 46], the arcus tendineus levatoris ani (muscular white line) [45, 46], the uterosacral ligament and the cardinal ligament [45, 47].

Pelvic floor muscles

The pelvic floor muscles consist of several muscle layers [48]. The deep muscle layer is formed by the levator ani and the coccygeus muscle. Together with their associated fascia this layer is called the pelvic diaphragm [44, 48, 49]. Some anatomists also include the external anal sphincter to the muscles of the pelvic diaphragm [49]. Below the pelvic diaphragm are the deep transverse perinei, compressor urethrae and sphincter urethrovaginalis muscles and the superficial perineal muscles [40].

Levator ani muscle

The levator ani muscle is a fan-like layering of striated muscles [12, 50]. It is the largest component of the pelvic floor musculature and consists of several subdivisions (Figure 1). There is some disagreement regarding the nomenclature to be used on the subdivisions [51, 52]. However, there are three basic portions of the levator ani muscle [9].

The medialmost muscle portion that arises from the pubic bone and inserts onto the vaginal wall (pubovaginal muscle), into the perineal body (puboperineal muscle) and into the intersphincteric groove (puboanal muscle) [9, 51] is often called the pubococcygeus muscle [53]. Some authors are in favour of the term “pubovisceral muscle” for this muscle portion [51, 52]. Other authors define the pubovisceral muscle as the combination of the pubococcygeus and puborectalis muscle portion [8, 47, 54].

The muscle portion that arises from the pubic bone, laterally from the pubococcygeus muscle, [55] and inserts into the fibres of the opposite side to form a sling behind the rectum is called the puborectalis muscle [8, 51, 53].

The lateral part of the levator ani muscle, which arises from the acrus tendineus levatoris ani and inserts in the anococcygeal raphe is called the ileococcygeus muscle [51]. It spans the opening in the posterior pelvis from one pelvic sidewall to the other [37, 47, 56].

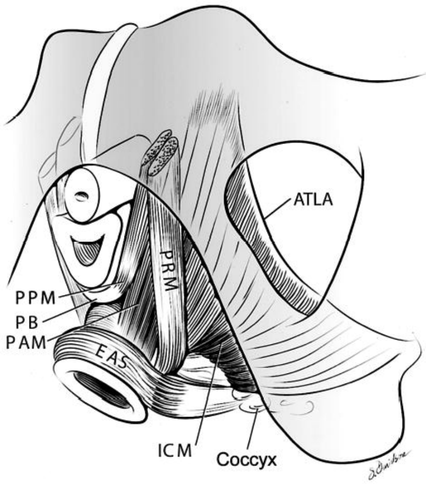

Figure 1: Schematic view of the levator ani muscles from below after the vulvar structures and perineal membrane have been removed showing the arcus tendineus levator ani (ATLA); external anal sphincter (EAS); puboanal muscle (PAM); perineal body (PB) uniting the 2 ends of the puboperineal muscle (PPM); iliococcygeal muscle (ICM); puborectal muscle (PRM). Note that the urethra and vagina have been transected just above the hymenal ring. Copyright © DeLancey 2003.

From Obstet Gynecol 2004; 104(1):168-73; Kearney R et al.; DOI: 10.1097/01.AOG.0000128906.61529.6b
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Levator hiatus and levator plate

The part of the levator ani muscle which originates from the pubic bone on either side, the pubococcygeous and puborectalis muscle, the symphysis pubis and the pubic bones form the levator hiatus [8]. It allows for the passage for the urethra, the vagina and the rectum [6, 8]. The levator hiatus is the largest potential hernia portal in the human body [6, 7]. The fusions of the muscle fibres of the levator ani muscle in the midline between the anus and the coccyx is called levator plate [57, 58].

Innervation

The levator ani and the coccygeus muscle receive innervation which originates from the sacral foramina three, four and/or five [43, 59, 60]. The pudendal nerve, which originates from the sacral foramina two, three and four innervates the external urethral and anal sphincter and the superficial perineal muscles [59]. However, there is some controversy about whether the levator ani muscle also receives some innervation from some branches of the pudendal nerve [61].

2.1.2 Function and dysfunction

Pelvic floor function

Normal pelvic floor function depends on the coordinated action between the above-mentioned structures of the pelvic floor [8, 56]. One of the main functions of the pelvic floor is maintaining pelvic organ support and continence, provided by the interaction between the pelvic floor muscles and the supportive connective tissue (the endopelvic fascia and the supportive ligaments) [9, 47, 56]. Yet, normal pelvic floor function must also enable the storage and elimination of urine and faeces as well as intercourse and childbirth [8, 9, 39].

Levator ani muscle function

The levator ani muscle differs from most other skeletal muscles in that it constantly contracts [8, 9, 62, 63], which keeps the levator hiatus closed [8, 9, 37]. For voiding, defaecation and during delivery relaxation of the levator ani muscle is essential [39, 62-64]. With a loss of tone in the levator ani muscle there is a sagging of the levator plate and an enlargement of the levator hiatus [44, 65]. In this situation the pelvic organs are only held in place by the supportive connective tissue, which can only sustain these loads a short period of time [8, 9].

Pelvic floor dysfunction

Any abnormalities in the pelvic floor structures and function might result in the development of “pelvic floor dysfunction”, a term applied to a variety of clinical conditions, including urinary incontinence, anal incontinence, pelvic organ prolapse, abnormal evacuation, sexual dysfunction and chronic pelvic pain [20]. Often the term refers to the first three [8] because they are the most definable and common conditions found by clinicians [20].

Levator ani muscle dysfunction

If the levator ani muscle is damaged, the connective tissue has to take over the increased load (8, 9, 48). The connective tissue may also become damaged over time and potentially fail to hold the organs in place [8, 9, 47]. The analogy of a ship suspended in the dockside with ropes is used to describe this condition [66, 67]. Once the water is gone (for example the levator ani muscle is damaged), the ropes (for example the ligaments) would be stretched, unable to take the additional burden over extended periods of time. Thus pelvic organ prolapse might occur [9, 66, 67].

Prevalence of pelvic floor dysfunction

Pelvic floor dysfunction is an important health issue [25, 68]. These debilitating conditions affect the quality of life of many women and impact on the healthcare system and costs [24-26, 68]. The prevalence varies widely according to the definition used and population studied. However, large population-based studies find that at least one-third of adult women are affected by one or more dysfunctions [68-70]. Further, 11-20% of women in western countries undergo surgery for pelvic organ prolapse or urinary incontinence during their lifetime [71-73], and up to 30% require repeat operations [71]. In the United States the annual costs associated with ambulatory care for pelvic floor dysfunction was estimated to be $412 million in 2006 [74].

Etiology of pelvic floor dysfunction

The etiology of pelvic floor dysfunction is believed to be complex and multifactorial [20, 21]. Rather than one single factor, a combination of anatomical, physiological, genetic, lifestyle and reproductive factors might contribute to pelvic floor dysfunction throughout a woman's lifespan [20, 21, 75-79].

Vaginal childbirth has been put forward as the strongest risk factor for the development of pelvic floor dysfunction [23, 79]. However, it might not be the fact of childbirth per se, but the injuries which occur during the process of labour that increase the risk of developing pelvic floor dysfunction directly after childbirth or later in life [21].

The childbirth-related injury to each pelvic floor structure and the mechanisms behind it must be considered separately, since the different structures have different functions in the pelvic organ support- and continence-system [21]. For example, anal sphincter injury is linked to anal incontinence [80, 81], fascial defects of the rectovaginal septum may lead to the appearance of a rectocele [27, 82], whereas nerve damage might be associated with both urinary and anal incontinence [83-85]. Several studies show an association between childbirth-related injuries of the levator ani muscle, such as major levator ani muscle defects and both pelvic organ prolapse, and prolapse recurrence after pelvic reconstructive surgery [22, 86-94].

2.3 Pelvic floor during pregnancy

During pregnancy the pelvic floor tissue undergoes dramatic adaptations [95-100], presumably in preparation for vaginal delivery, hence facilitating the passage of the fetus and in minimising the risk of childbirth-related injuries [101-103]. The increasing pressure of the growing uterus and fetal weight, altered progesterone-, estrogen- and relaxin-levels as well as quantitative and qualitative alterations in collagen levels have been discussed as factors contributing to the change [104-106]. It seems that the pregnancy-related changes of the pelvic floor lead to a reduction of pelvic organ support [97-100, 107] and a widening of the levator hiatus [100, 108].

2.4 Process of childbirth

2.4.1 Normal labour and delivery

Childbirth includes both labour (the process of birth) and delivery (the birth itself) [109]. Normal labour refers to the entire process as a fetus makes its way from the uterus down the birth canal to the outside world.

Mechanisms of normal labour and delivery

Delivery depends on the complex interaction of three mechanical variables, known as the "three Ps": the power, the passenger, and the passage [5, 110, 111].

The **power** refers to the force generated by the uterine musculature during contractions, which results in dilatation of the cervix and voluntary bearing-down efforts leading to the expulsion of the fetus through the birth canal [110].

The **passenger** is the fetus. There are several fetal variables that can affect the course of labour: fetal size, position and presentation [110].

The **passage** is the birth canal, which consists of the bony pelvis and the soft tissues, for example, the cervix and the pelvic floor musculature [110], especially the levator ani muscle [50, 112]. These structures generate varying degrees of resistance to fetal expulsion [50, 113].

In humans there is an asymmetry in both the shape of the maternal bony pelvis and the fetal head [1, 3, 109]. The birth canal has an irregular form and its axis does not follow a straight line but curves upwards, first described by Carl Gustav Carus in 1820 [1] (Figure 2). In addition, the heads of human fetuses have relatively large dimensions relative to the maternal pelvis [1-3, 5, 109]. So it is evident that the fetal head cannot pass through the birth canal without a process of adaptation and accommodation (so-called “cardinal movements” of the fetus) [3, 50, 109, 111], in order to always present its smallest achievable diameter to the most favourable pelvic diameters [109, 112]. Thereby, delivery proceeds along the line of least resistance [50, 109].

Figure 2: Fetus in vertex presentation, defined as the fetal head positioned to emerge first before the rest of the body at delivery. The red arrow describes the curve of Carus.

From: Smellie W. Vertex presentation, occiput anterior (Plate 14, from "A Set of Anatomical Tables with Explanations") [1792]

Stages of normal labour

Childbirth has traditionally been divided into three stages [111]. The active first stage of labour refers to the interval between the onset of labour and complete cervical dilatation [111, 113, 114]. The second stage of labour begins when the cervical dilatation is complete and ends with expulsion of the fetus [111, 113, 114]. Second stage is characterised by descent of the presenting part of the fetus through the maternal pelvis [113]. International guidelines differ in their definitions of the normal length of second stage. The American College of Obstetricians and Gynecologists recommends that the diagnosis of prolonged second stage should be considered, when the duration of second stage exceeds two hours for primiparous women, when no regional anaesthesia is used, and three hours when regional anaesthesia has been administered [110]. The third stage of labour refers to the time from fetal delivery to expulsion of the placenta [111, 113].

2.4.2 Complicated deliveries

The two-hour rule of the length of second stage of labour goes back to the mid-1800s, and was based on expert opinions and case series publications [115]. Since that time, the second stage of labour was thought to be a risk period for maternal and neonatal morbidity and mortality [115-118].

In 1920, Joseph DeLee [118] recommended the prophylactic use of forceps to shorten the second stage of labour to reduce complications to mother and the fetus and his paper contributed considerably to a change in clinical practice towards active shortening of the second stage of labour over many decades [119]. Continuous improvement in fetal monitoring and neonatal care have attenuated previous concerns relating to the length of the second stage of labour on infant morbidity and mortality [116]. To date, several studies suggest that adverse events to the fetus might be more related to instrumental interventions during delivery than to the length of the second stage itself [115, 120, 121].

The concern that prolonged second stage of labour is a risk period for maternal complications is still justified. Several recent studies show that prolonged second stage of labour is associated with postpartum haemorrhage, fever or infection and pelvic floor injuries [14, 115, 116, 122-126]. Women with prolonged second stage undergo an increased number of instrumental vaginal deliveries: vacuum and/or forceps [116, 117, 124], which in turn are also linked to the above-mentioned maternal complications [80, 122, 123, 126-130]. Furthermore, women might not only suffer somatic trauma. There is evidence that there might also be psychological trauma associated with complicated deliveries [15].

2.4.3 Levator ani muscle during childbirth

As part of the birth canal, the levator ani muscle is one of the tissue structures defining its dimensions and generating resistance/forces on the fetal head [112, 131]. Several computational models have been developed to understand the complex interaction of the maternal pelvic floor muscles and fetal head motion during the second stage of labour [11, 109, 112, 131-133]. It is assumed that the fetal head initially makes contact with the iliococcygeal muscle portion approximately after it has descended one centimetre inferior to the ischial spines [11, 133]. With further descent the levator ani muscle wraps around the fetal head, is displaced in a cranio-caudal direction and is also stretched considerably [11, 133]. The levator hiatus widens and lengthens [133]. The further the fetus descends and presses against the pelvic floor, the higher the forces generated by the pelvic floor tissue [3, 112, 113]. These forces significantly influence the fetal cardinal movements [3, 112, 113]. When the fetal head extends and expulses through the levator hiatus and the vulvar opening (so-called “crowning”) stretch-ratios of 3.5 times the resting length have been estimated for the medialmost muscle portion (pubococcygeous/pubovisceral) [11, 132, 133].

However, there are great inter-individual variations in the levator hiatus dimensions, and the tissue distention needed for vaginal delivery might therefore vary greatly between women [10]. Transperineal ultrasound data assessed in late pregnancy showed that the stretch of the medialmost levator ani muscle portion required for vaginal delivery varied between 67% and 276% among women when calculated from resting length [10].

2.4.4 Childbirth-related pelvic floor injuries

Mechanisms of childbirth-related pelvic floor injuries

The mechanisms of childbirth related injuries have not been fully determined [37]. It is likely that the stretching that some pelvic floor structures undergo during childbirth may result in injuries to the structures under stress, for example the levator ani muscle [11, 18, 19], the anal sphincter [80] and the pelvic floor nerves [134]. An alternative mechanism to the pelvic floor impairment occurring during delivery is long-lasting tissue compression through the fetal head, which might cause hypoxia damage [9, 135-137].

Major levator ani muscle defects and irreversible overdistention

Excessive stretching is a well-known cause of striated muscle injury [9, 138]. Physiology research suggests that a skeletal muscle will suffer substantial trauma if it is stretched beyond 1.5 of its resting length [138]. Some of the estimated maximum stretch ratios for the different portions of levator ani muscle that occur during crowning of the fetal head exceed those values considerably [10, 11, 133]. It is not surprising, therefore, that the degree of distension occurring during delivery may result in the tearing of parts of the levator ani muscle from its bony insertion [11, 18, 19]. In literature, different terminology is used to describe this condition: major levator ani muscle defects, avulsion, full avulsion and levator ani muscle trauma or muscle tear are often used synonymously [18, 19, 122, 125, 128, 139, 140]. Imaging studies among primiparous women have shown that major levator ani muscle defects could occur in 13-36% of the women [18, 19, 122, 125, 139]. The excessive stretching might also cause an irreversible traumatic overdistention of the levator ani muscle which leads to an increase in levator hiatus area during Valsalva manoeuvre of more than 20% between two examinations performed pre- and postpartum [6, 122].

Risk factors for childbirth-related pelvic floor injuries

Several factors influence whether a woman sustains childbirth-related injuries to the pelvic floor [21]. Large fetus, large fetal head circumference [125, 130, 141] and the length of second stage of labour and instrumental intervention during vaginal delivery increase the risk of injuries to different structures of the pelvic floor. The length of second stage of labour and instrumental intervention during vaginal delivery have particularly been found to be associated with major levator ani muscle defects [86, 122, 123, 125, 128], irreversible overdistention [122], severe damage of pelvic floor muscle innervation [141, 142] and anal sphincter injuries [14, 80, 124, 126, 127, 129, 130].

Older maternal age at the time of the first delivery [123, 143] and low body mass index [28, 144, 145] have been discussed as risk factors for nerve injuries, anal sphincter injuries and major levator ani muscle defects occurring during delivery. Another potential maternal risk factor for childbirth-related injuries might be the woman's pelvic floor anatomy. Handa et al. found significantly more anal sphincter injuries among certain racial and ethnic groups, which might be attributable to differences in the perineal anatomy [130]. Significant architectural differences in the bony pelvis in women with and without pelvic floor disorders have been found [146, 147] and there has been speculation that the features of the bony pelvic architecture predispose women to pelvic floor injuries during childbirth [146].

2.5 Three- and four-dimensional transperineal ultrasound imaging

The lack of knowledge regarding the influence of the antenatal levator hiatus dimensions on delivery outcome depends largely on the fact that the levator ani muscle has not been easy to study as it lies hidden from surface anatomy. Up until recently, pelvic floor ultrasonography was limited to the sagittal plane [(148)]. For the visualisation of the levator hiatus, the surrounding levator ani muscle and the muscle attachment to the pubic bone, access to the axial plane is necessary. Access to the axial plane was previously reserved to magnetic resonance imaging [(149-153)]. But costs, access restrictions and contraindication of using magnetic resonance imaging during pregnancy have restricted the use of the method in clinical practice and for studying the pelvic floor in pregnant women [(54, 148, 153)].

Three- and four-dimensional transperineal ultrasound is more widely available, cost-effective and well tolerated by the women examined. Further, the real-time imaging allows evaluation of the functional aspects of the levator ani muscle [(148)]. Only four years before we started our study, Dietz et al. [(29)] published the first article about the dimensions of the levator hiatus using three- and four-dimensional transperineal ultrasound. Since this time, the method has been increasingly used to study the levator hiatus and its surrounding levator ani muscle.

Three-dimensional transperineal ultrasound of the levator ani muscle

Three-dimensional transperineal ultrasonography provides a multiplanar or orthogonal view [(29)]. It shows the three cross-sectional planes through the volume in question, each plane at a right angle to the other two [(38)]. The three orthogonal images, the sagittal, the axial and the coronal image are complemented by a rendered image (Figure 3) [(148, 154)].

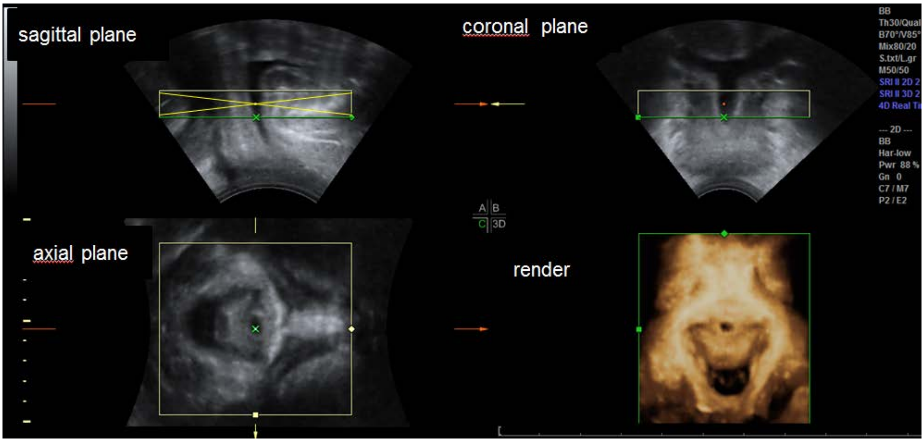


Figure 3: Presentation of the levator hiatus in three orthogonal planes and the rendered image of the axial plane. The yellow cross marks the render box. (Image by F. Siafarikas)

Four-dimensional ultrasound of the levator ani muscle

Four-dimensional imaging implies the real-time acquisition of the volume ultrasound data (148, 155), which enables the levator hiatus to be followed during pelvic floor muscle contraction and Valsalva manoeuvre (153, 154). This provides important qualitative and quantitative information on muscle function (148, 153, 155). For example, some women will not perform an optimal Valsalva manoeuvre when asked to do so (64). They require visual biofeedback to optimise their effort, which is easily possible with real-time imaging (156). The achieved sequences of ultrasound volume blocks are called “cineloops” and can be stored on the ultrasound machine or on an external hard disk (148, 155).

Post-processing and offline analysis

Post-processing and analysis of ultrasound volumes are possible immediately on the actual ultrasound machine or on a personal pc/laptop with the help of dedicated software at a subsequent date (38, 148, 155). The offline analysis allows the measurement of the size of the levator hiatus, the so-called "levator hiatus dimensions" in any user defined plane and the re-enactment of the manoeuvres [156].

Volume rendering

Rendering algorisms are supposed to improve image resolution [38] by reducing the speckle artifacts of the image by filling up the gaps with tissue information from the adjacent layers [38, 157, 158]. For pelvic floor ultrasonography, rendering such as *volume contrast imaging* or *render mode* is an important feature to account for the non-Euclidean shape of the levator hiatus (Figure 4) [159, 160]. During the Valsalva manoeuvre the levator ani muscle distends both laterally and caudally. Measurements of the levator hiatus in a single slice may lead to overestimation, because the true dimensions may lie caudal to the single slice "flat" plane [159, 160].

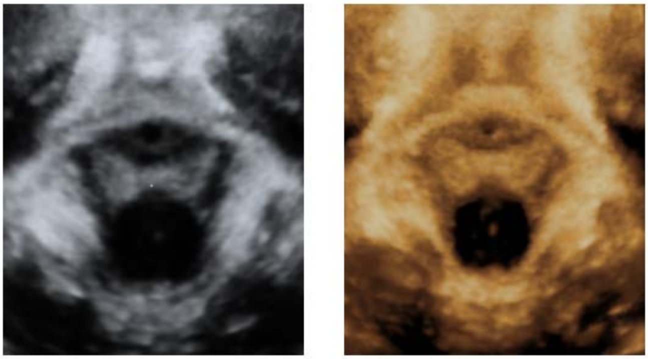


Figure 4: Presentation of the levator hiatus at rest using volume contrast imaging (left-hand side) and render mode (right-hand side). *(Images by F. Siafarikas)*

Tomographic ultrasound imaging

With tomographic ultrasound imaging it is possible to process imaging information within an area of interest into slices [38] (Figure 5). It allows the evaluation of the integrity of the attachment of the muscle into the pubic bone over the entire craniocaudal extent of muscle insertion [139, 155]. Thus it is used to diagnose major levator ani muscle defects.

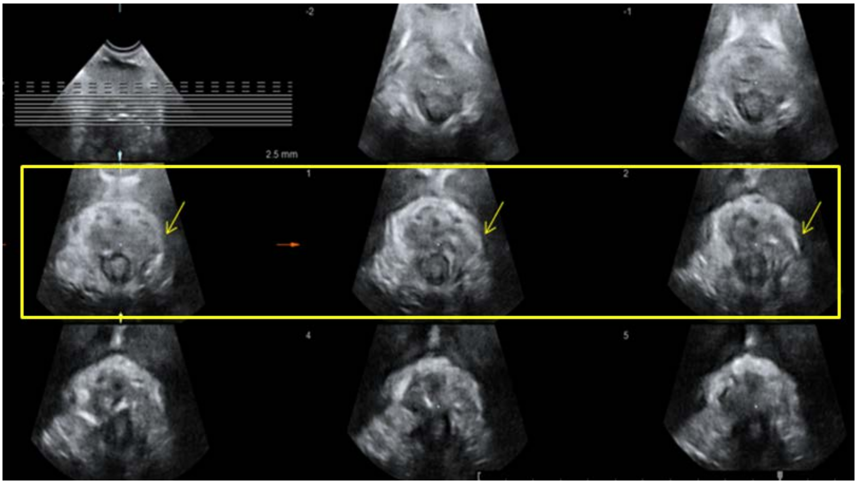


Figure 5: Tomographic ultrasound imaging of the levator hiatus acquired 6 weeks after vaginal delivery. The yellow arrow visualises a major levator ani muscle defect on the left-hand side in the three central slices. The three central slices are highlighted by the yellow box.

From BJOG; 2015;122(8):1083-91; Siafarikas F et al; DOI: 10.1111/1471-0528.13332

2.5.1 Learning process

It has been stated that volume acquisition can easily be learned but that offline analysis might be more challenging [38]. However, at the time of launching our study, a search on PubMed did not reveal any studies regarding the learning process of volume acquisition and the offline analysis of three- and four-dimensional ultrasound data of the levator hiatus.

2.5.2 Reliability and validity

Reliability and validity of levator hiatus dimensions and functional aspects of the levator ani muscle

Between 2005 and 2009, several papers on the intra- and inter-rater reliability of the levator hiatus dimensions at rest and during pelvic floor muscle contraction and Valsalva manoeuvre have shown acceptable reliability [29, 30, 32-35]. However, all studies only measured reliability for the process of offline analysis, since the measurements were taken on previously stored datasets acquired by one single investigator. By using stored datasets, the source of variability in the measurements due to the process of volume acquisition was not taken into account [36]. There was a lack of studies that had tested the reliability between two independent investigators for the complete transperineal ultrasound technique including instructing the patient, volume acquisition and analysing the ultrasound volumes offline.

Sonographic measurements of the levator hiatus dimension have been tested against levator hiatus measurements using magnetic resonance imaging, which was the gold standard of levator hiatus imaging and found to be valid [54, 153]. Clinically, an association between levator hiatus dimensions and symptoms and signs of prolapse has been found [7, 94, 161].

Pelvic floor muscle function has traditionally been evaluated by palpation, manometry/dynamometry, electromyography, or with ultrasonography in the sagittal plane and usually refers to activity of the muscle during contraction [162-164]. To evaluate the functional aspects of the levator ani muscle by using levator hiatus measurements in the axial plane, the calculation of percentage muscle-length shortening during maximum pelvic floor contraction relative to resting state was suggested [34, 165]. However, in pregnant women the assessment of the levator ani muscle ability to stretch might also be of importance, as one could assume that a more stretchable levator ani muscle antenatally might be preferable in order to minimise the risk of injuries during delivery [165]. Thyer et al. [165] proposed the estimation of the percentage increase in muscle-length during the Valsalva manoeuvre relative to resting stage as a surrogate for muscle-elasticity/distensibility and showed acceptable reliability for measurements. Moderate correlation between muscle-length decrease during contraction as well as weak correlation between muscle-length increase during Valsalva manoeuvre and digital palpation was found [165]. By assessing the percentage change in muscle-length during manoeuvres it is possible to adjust for differences in resting state. This may provide a more complete picture of the levator ani muscle function than the absolute measurements of levator hiatus area during contraction and Valsalva manoeuvre, alone.

Reliability and validity of major levator ani muscle defects

In urogynaecological populations good reliability for diagnosing major levator ani muscle defects has been shown [22, 90]. The presence and extent of major levator ani muscle defects diagnosed using magnetic resonance imaging and transperineal ultrasound were found to be associated with symptoms and signs of pelvic organ prolapse, especially of the anterior and central compartment [22, 86, 87, 90], and prolapse recurrence after surgical correction [27, 88, 89, 91-93]. Tomographic ultrasound imaging has become the *de facto* standard in diagnosing major levator ani muscle defects using three- and four-dimensional ultrasound [166]. It has been shown that abnormal insertion of the levator ani muscle presentable in the three central slices correlates best with clinical signs of pelvic organ prolapse in urogynecological populations [167].

3 Aims of the thesis

I. To monitor the learning process for acquiring three- and four-dimensional transperineal ultrasound volumes and for their offline analysis. Further, to perform an interobserver reliability study of the entire ultrasound procedure, including both ultrasound volume acquisition and offline analysis for two investigators.

II. To study the associations between levator hiatus dimensions measured with three- and four-dimensional transperineal ultrasonography at 37 weeks of gestation and both the length of passive and active second stage of labour and also the delivery mode in women delivering their first child.

III. To investigate associations between the antepartum levator ani muscle measurements listed below and major levator ani muscle defects at 6 weeks postpartum in women delivering their first child:

- levator hiatus area at rest, during maximal pelvic floor muscle contraction, and during the Valsalva manoeuvre
- the percentage decrease in length of the levator ani muscle from rest to maximal pelvic floor muscle contraction, assuming that a higher percentage of muscle shortening represents more efficient contraction of the levator ani muscle
- the stretch of the muscle expressed as the percentage increase in muscle length from rest to Valsalva manoeuvre, assuming that a higher percentage of muscle lengthening represents a more stretchable levator ani muscle

4 Material and methods

4.1 Study design

All three papers were based on data of a prospective cohort study performed at Akershus University Hospital in collaboration with the Norwegian School of Sport Sciences, with the overall aim of exploring anatomical and functional changes in the pelvic floor during pregnancy and postpartum in nulliparous women having their first child.

Information about the study was sent out via post to all nulliparous women, applying for a birthplace at Akershus University Hospital, together with an invitation for the routine ultrasound examination at 18 weeks of gestation. When the women attended the routine ultrasound at 18 weeks of gestation they were contacted by a project coordinator and asked to participate. Between December 2009 and April 2011, 300 nulliparous pregnant women were recruited. The cohort study ran from mid-pregnancy until 12 months postpartum and included assessment appointments at approximately 22 and 37 weeks of gestation and 6 weeks, 6 months and 12 months post-partum.

At each visit the women were examined using three- and four-dimensional transperineal ultrasound. The offline analysis included the assessment of levator hiatus dimensions in the axial plane, pelvic organ mobility in the sagittal plane and the diagnosis of major levator ani muscle defects. The women underwent a standardised gynaecological examination to quantify pelvic organ support using the pelvic organ quantification system and answered an electronic questionnaire on pelvic floor symptoms. In addition, pelvic floor muscle function was assessed by observation of the perineum, palpation and manometry (except at gestational week 37). Several papers using data from the cohort study have been published (Appendix).

The three papers included in this thesis use ultrasound data obtained at 22 and 37 weeks of gestation and 6 weeks postpartum, as well as demographic and obstetric data from the questionnaire and the hospital's electronic birth records.

4.1.1 Power calculation

The present studies were a planned part of a project addressing several questions related to the pelvic floor during pregnancy and in the postpartum period. Whereas the power calculation for the 300 women in the cohort study was based on the power calculation for detecting changes of levator hiatus dimension at rest from a previous study [168, 169], no specific power calculation was performed for the studies included in this thesis.

4.1.2 Inclusion criteria

Inclusion criteria were being over 18 years old, having a singleton pregnancy and being able to understand one of the Scandinavian languages. Exclusion criteria were a previous pregnancy of more than 16 weeks of gestation, premature birth < 32 weeks of gestation in the ongoing pregnancy, stillbirth and serious illness of mother or child that may interfere with participation in the follow-up.

Additional exclusion criteria for Paper II were: pre-labour caesarean section and caesarean section before full cervical dilatation, as well as missing delivery data registered in the hospital's electronic birth records. The rationale for the latter exclusion criteria was that in women who did not deliver at the Akershus University Hospital the accurate estimation of delivery duration was not possible.

Additional exclusion criteria for Paper III were pre-labour caesarean section and caesarean section before full cervical dilatation.

4.1.3 Ethics

The Regional Ethics Committee (REK Sør-Øst D 2009/170) and the Data Protection Officer (2799026) approved the study, and all women gave their informed written consent to participate.

4.2 Data collection

4.2.1 Ultrasound measurements

Apparatus

Volume acquisition was performed using a GE Voluson E_8 system (GE Medical Systems, Zipf Austria) with 4-8 MHz curved array three- and four-dimensional ultrasound transducer (RAB4-8l/obstetric). The field of view angle was set to its maximum of 70º in the sagittal plane and the acquisition angle was set to 85º in the coronal plane [35, 54].

Volume acquisition

Before volume acquisition the women had all been instructed by a physiotherapist on how to perform a correct pelvic floor muscle contraction. The correctness of the manoeuvre was assessed by vaginal palpation and was defined as an inward movement and closure around the pelvic openings [41, 170]. The ultrasound volumes were acquired with the women in the lithotomy position, with an empty bladder [35, 54]. The ultrasound probe was covered with a condom and firmly placed on the perineum in the sagittal plane [54]. The standard midsagittal view included the symphysis pubis, the urethra and bladder neck, the vagina, rectum, and anal canal and the levator plate [38, 154]. The women were asked to perform three maximum pelvic floor muscle contractions and three maximum Valsalva manoeuvres. The Valsalva manoeuvre was performed for at least six seconds [171]. Verbal instructions, biofeedback using ultrasound and repetition were used to receive optimal Valsalva manoeuvre and avoid co-contraction of the most medial part of the levator ani muscle during the manoeuvre [64, 171]. The ultrasound volumes were stored on an external hard-disk and analysed offline at a subsequent date.

Offline analysis

The offline analysis was performed on a laptop using 4DView version 10 (GE Medical Systems) software. All ultrasound volumes acquired for each woman were previewed from the investigator performing the offline analysis and only the manoeuvre with the best contraction and the most efficient Valsalva manoeuvre was analysed. The analysis was performed in the plane of minimal hiatal dimension, which is the plane with the minimal distance between the hyperechogenic posteroinferior margin of the symphysis pubis and the anterior border of the levator ani muscle at the anorectal angle in the midsagittal plane [29, 33, 54]. The volume with the best contraction was defined as the one with the shortest anteroposterior diameter from the symphysis pubis to the levator ani muscle and the most cranial displacement of the bladder-neck and levator ani muscle in the plane of minimal hiatal dimension [167-169]. The volume with the most efficient Valsalva manoeuvre was defined as the one with the largest anteroposterior diameter and the most caudal displacement of the bladder-neck and levator plate in the plane of minimal hiatal dimension [167-169]. Rest position was defined as the most caudal position of the levator ani muscle before contraction.

Levator hiatus dimensions in the axial plane

When the volume with the best manoeuvre was found, the axial dimensions of the levator hiatus using volume contrast imaging (Paper I) or render mode (Paper II and III) were estimated. Using volume contrast imaging a slice thickness of 2 mm was chosen. Using render mode the render box which was applied around the plane of minimal hiatal dimension in the mid-sagittal plane was approximately 1.5 cm thick.

The following levator hiatus dimensions were assessed: levator hiatus area, the levator hiatus circumference, anteroposterior and transverse diameter, the levator-urethra gap and pubic arch (Figure 6).

The **levator hiatus area** was measured as the area bordered by the levator ani muscle, the symphysis pubis and the inferior ramus pubis [33, 35]. The **levator hiatus circumference** was measured as the linear distance around the edge of the levator hiatus area. The **anteroposterior diameter** was the anterior-posterior distance between the symphysis pubis and the levator ani muscle. The **transverse diameter** from right to left was defined as the widest part of the levator hiatus, perpendicular to the anteroposterior diameter [33]. The **levator-urethra gap** was measured from the insertion of the levator ani muscle on the left and right sides to the midurethra [172]. The **pubic arch** was obtained during contraction and measured along the inner margin of the pubic ramus between the insertions of the levator ani muscle into the pubic bone [165].

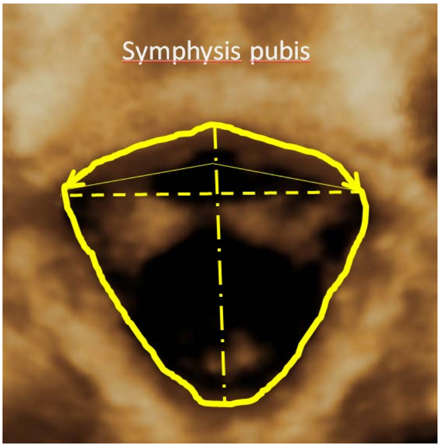


Figure 6: Levator hiatus dimensions in the axial plane during maximum pelvic floor muscle contraction
Fat solid line: levator hiatus circumference/ bordering the levator hiatus area, broken dotted line: anteroposterior diameter, broken line: transverse diameter, thin solid line: levator-urethra gap, pubic arch: distance between the two arrows (Image by F. Siafarikas)

Major levator ani muscle defects

Major defects of the levator ani muscle were assessed using tomographic imaging of the axial plane during maximal levator ani muscle contraction. If the woman was unable to contract, the rest volumes were used to assess muscle integrity. The plane of minimal hiatal dimensions of the levator hiatus was used as the reference plane [139, 173]. Tomographic slices were obtained at 2.5 mm slice intervals from 5 mm caudally to 12.5 mm cranially to the reference plane, producing eight slices [139, 167, 173]. As suggested by Dietz et al. [167], major defects of the medial part of the levator ani muscle were diagnosed when an abnormal insertion of the muscle into the pubic bone was present in all three central slices at the plane of minimal dimension, and 2.5 mm and 5.0 mm cranially to it (Figure 5, page 27).

Reliability of volume acquisition

There were two investigators performing the volume acquisition. One investigator was a senior gynaecologist with extensive experience of examining the pelvic floor using transperineal ultrasonography. The second investigator followed a structured learning programme on transperineal ultrasound examination. Excellent reliability for the volume acquisition between the two inverstiagtor was found [(174)]. The learning process is described in Paper I [(174)].

Reliability of offline analysis

The two investigators who performed the volume acquisition also performed the major part of the offline analysis. The learning process for the offline analysis and the interobserver reliability for the entire ultrasound procedure are described in Paper I [(174)]. Additionally two physiotherapists analysed the ultrasound volumes. The interobserver reliability between the four investigators was calculated pair-wise using 50 datasets and intraclass correlation between 0.62 and 0.98 for the levator hiatus dimensions with acceptable limits of agreement were estimated (*data not published*). There was no significant bias between the four investigators.

Reliability of major levator ani muscle defects

Evaluation of major levator ani muscle defects was performed by the two investigators, who also performed the volume acquisition. The interobserver reliability between them was calculated for diagnosing major levator ani muscle defects at 6 weeks' postpartum and was found to be good to excellent (kappa range from 0.63 to 0.91) [(173)].

4.2.2 Demographic data

Demographic data, such as age, height and pre-pregnancy weight was obtained at the first visit at 22 weeks of gestation via an electronic questionnaire.

4.2.3 Obstetric data

Obstetric data was collected from the hospital's electronic birth records. Ten women had not delivered at the Akershus University Hospital. They underwent a telephone interview regarding delivery process and were asked for information on: delivery mode, indication for instrumental intervention, induction of labour, labour augmentation, episiotomy, perineal tears, fetal birth weight and fetal head circumference.

Delivery mode

Delivery mode was classified as normal vaginal delivery, instrumental vaginal delivery (vacuum and forceps) and caesarean section as pre-labour caesarean section, caesarean section before and after full cervical dilatation.

Delivery duration

Partogram data in the hospital's electronic birth records were used to estimate the duration of the first and second stage of labour. The duration of the active first stage of labour was defined as the time interval between a cervical dilatation of equal or more than three centimetres until complete cervical dilatation [111, 113, 114]. The duration of the second stage of labour was the time interval between complete cervical dilatation and delivery of the child [111, 113, 114]. The second stage of labour was further divided into passive and active second stage. Passive second stage was defined as the interval between complete cervical dilatation and the commencement of active pushing [50]. Active second stage was defined as the time of active pushing until delivery of the baby [50].

Other obstetric data

Other obstetric data such as induction of labour was coded "yes" or "no". Epidural analgesia (yes/no), was given as continuous infusion the possibility of administration of additional epidural dosages. Labour augmentation (yes/no) included amniotomy, oxytocin administration and breast stimulation. Episiotomy (yes/no) was performed as a left-sided medio-lateral episiotomy.

Fetal data

The hospital's electronic birth records provided date on offspring birth weight and fetal head circumference.

4.2.4 Timing of clinical visits

The clinical visit at 22 weeks of gestation was chosen because we wanted to examine the women as early as possible following their informed consent after they attended the hospital for the recommended and state-financed routine prenatal ultrasound examinations at 18 weeks of gestation. This allowed us to invite all women who fulfilled the inclusion criteria and were likely to give birth at our hospital. The examination at 37 weeks of gestation was chosen because, on one hand, we wanted to study the levator ani muscle closest in time to delivery and, on the other hand, we wanted to avoid high volumes of missing data resulting from delivery before the ultrasound examination. We choose the six weeks' follow-up for diagnosing major levator ani muscle defects for practical reasons. In Norway, women have routine postpartum examination six weeks after delivery. It was therefore convenient for the participants to have the study follow-up examination at the same time.

4.2.5 Blinding

The investigators were blinded to the women's demographic data and obstetric history. The ultrasound images were stored offline using anonymous code numbers and analysed in random order. At the postpartum appointment, the women's abdomens were covered by sheets and they were asked not to divulge any information regarding their deliveries.

4.3 Study design, participants, outcome measurements and statistical analysis for papers I-III

4.3.1 Paper I

Study design

Reliability study

Participants

22 women (two nulliparous pregnant women at 22 weeks of gestation, 10 nulliparous pregnant women at 37 weeks of gestation, and 10 primiparous women 6 weeks after delivery) participating in the cohort study were included. In addition, four staff volunteers were recruited.

Investigators

Experienced investigator

The experienced investigator was a senior gynaecologist with extensive experience of performing volume acquisition and offline analysis of three- and four-dimensional transperineal ultrasound data.

Inexperienced investigator

The inexperienced investigator was a physician undergoing her 4th year of specialist training in gynaecology and obstetrics. She was comfortable with performing transvaginal and abdominal ultrasound examinations but had no previous experience in examining the pelvic floor with three- and four-dimensional transperineal ultrasound.

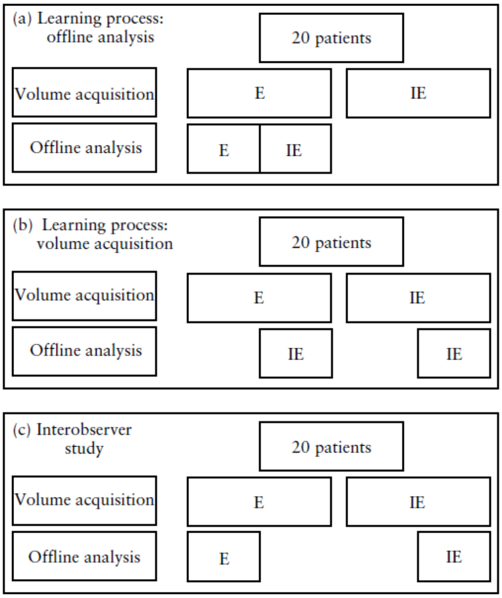
Teacher

Both the inexperienced and the experienced investigators were taught by a member of the research group who had extensive experience in volume acquisition and offline analysis of transperineal ultrasound data [33-35, 54].

Learning procedure

An initial introduction procedure was performed in which the inexperienced investigator became familiar with the ultrasound machine, issuing instructions to the women and how to record three ultrasound volumes of the pelvic floor during pelvic floor contraction and Valsalva manoeuvres using the four staff volunteers. Thereafter, the inexperienced investigator was instructed on how to use the 4D-View-analysis software, how to find the image with the best contraction, most effective Valsalva manoeuvre and how to measure the levator hiatus dimensions in the chosen image in the axial plane. To evaluate the introduction procedure, the inexperienced and the experienced investigator both acquired levator hiatus dimensions on the same two women at 37 weeks of gestation and analysed the recorded volumes. It was stated *a priori,* that the dispersion between the measurements between both investigators should not exceed 10% for the inexperienced investigator to be allowed to continue the learning procedure.

After the introduction procedure the inexperienced and experienced investigator performed volume acquisition on the remaining 20 women. Each woman was examined twice, once by the inexperienced and once by the experienced investigator, consecutively and in alternating order. The ultrasound volumes acquired by the experienced investigator were analysed by both investigators and the ultrasound volumes acquired by the inexperienced investigator she then analysed herself (Figure 7).



(a) Learning process of offline analysis:
The inexperienced examiner (IE) and the experienced examiner (E) analysed volumes recorded by E.

(b) Learning process of volume acquisition:
IE analysed volumes recorded by E and IE.

(c) Interobserver study:
Each investigator analysed her own recorded volumes.

Figure 7: Diagram illustrating the learning procedure of an inexperienced examiner in performance of three-dimensional transperineal ultrasound volume acquisition and offline analysis for measurement of levator hiatus dimensions, and the interobserver study between two independent examiners

From Ultrasound Obstet Gynecol. 2013;41(3):312-7; Siafarikas F et al; DOI: 10.1002/uog.11192

Outcome measurements

- Intraclass correlation coefficient for volume acquisition and offline analysis between an experienced and an inexperienced investigator in blocks of 10 examinations to evaluate the learning procedure/process.
- Interobserver reliability for the entire ultrasound technique including both volume acquisition and offline analysis

Study variables

The levator hiatus area, anteroposterior and transverse diameter, levator-urethra gap and pubic arch were assessed.

Statistical analysis

Statistical analysis was performed using SPSS version 18.0 (SPSS Inc., Chicago, IL, USA). To evaluate agreement between levator hiatus measurements between the two investigators, the intraclass correlation coefficient was calculated. Intraclass correlation values < 0.2 were considered poor, 0.21–0.40 were considered fair, 0.41–0.60 moderate, 0.61–0.80 good and 0.81–1.00 excellent [33, 35]. The mean difference between two measurements ("bias") and 95% limits of agreement (mean difference +/- (1.96 X standard deviation of the mean difference)) were calculated as described by Bland and Altman [175]. A two-way model was used. To test for systematic bias, a one-sample t-test was used to verify the hypothesis that the difference between the two investigators did not deviate from zero. $P < 0.05$ was considered statistically significant.

4.3.2 Paper II

Study design

Prospective cohort study

Participants

231 nulliparous women examined at 37 weeks of gestation.

Outcome measurements

- Duration of passive and active second stage of labour
- Delivery mode (normal vaginal delivery versus instrumental delivery)

The instrumental delivery group included all women having vacuum, forceps or caesarean section after full cervical dilatation.

Exposure measurements

Levator hiatus area, anteroposterior and transverse diameter at rest, during pelvic floor muscle contraction and Valsalva manoeuvre at 37 weeks of gestation.

Statistical analysis

Statistical analysis was performed using SPSS version 20 (SPSS Inc, Chicago, IL). Demographic and obstetric data were presented as frequencies with percentages, means with standard deviation (SD) for normally distributed data, or medians with ranges for non-normally distributed data. The correlation between levator hiatus dimensions and duration of active and passive second stage of labour was estimated using the Spearman correlation coefficient. Differences in levator hiatus measurements in women with normal vaginal and instrumental deliveries were given as the mean differences with 95% confidence intervals (95% CIs) and were analysed using the independent samples t-test. When analysing the influence of levator hiatus measurements on delivery mode, we used standard logistic regression analysis to control for possible covariates. Crude and adjusted Odds Ratios with 95% CIs were reported. P-values <0.05 were considered significant.

4.3.3 Paper III

Study design

Prospective cohort study

Participants

234 women examined at 21 and 37 weeks of gestation and at 6 weeks postpartum

Outcome measurement

Diagnosis of major levator ani muscle defects 6 weeks postpartum

Exposure measurements

- Levator hiatus area at rest, during pelvic floor muscle contraction and Valsalva manoeuvre at 21 and 37 weeks of gestation
- The percentage changes of the levator ani muscle-length during pelvic floor muscle contraction and Valsalva manoeuvre relative to resting state

Muscle-length was estimated by subtracting the length of the pubic arch from the levator hiatus circumference. It was assumed that a higher percentage of muscle shortening represents a more efficient contraction of the levator ani muscle and that a higher percentage of muscle lengthening represents a more stretchable levator ani muscle.

Statistical analysis

Statistical analysis was performed using SPSS version 20 (SPSS Inc, Chicago, IL). Demographic and obstetric data were presented as frequencies with percentages and means with SD for normally distributed data. Differences in levator hiatus measurements in women with and without major levator ani muscle defects were given as mean differences with 95% CIs and were analysed using an independent samples t-test. Standard logistic regression analysis was performed in order to control the findings for possible confounders. Crude and adjusted Odds Ratios with 95% CIs were reported. P-values <0.05 were considered significant.

5 Results

5.1 Paper I

Introduction procedure: For the volume acquisition the dispersion between the inexperienced and experienced investigator was less than 10% for all levator hiatus measurements after three one-hour learning-sessions, whereas four five-hour learning-sessions were needed for the offline analysis. Consequently, the introduction procedure was considered complete and the inexperienced investigator continued the learning procedure.

Learning-procedure of volume acquisition: The intraclass correlation coefficient between the inexperienced and experienced investigator ranged from 0.69 to 0.97 after the first 10 women who were examined. With the volume acquisition of the next 10 women, reliability between the investigators improved further (intraclass correlation coefficient range: 0.81- 0.97), especially for the measurements taken during the Valsalva manoeuvre.

Learning-procedure of offline analysis: After the first 10 offline analyses the intraclass correlation coefficient between the inexperienced and experienced investigator ranged from 0.13 to 0.94. The highest reliability was achieved for the measurements of the anteroposterior diameter and levator hiatus area during pelvic floor muscle contraction (intraclass correlation coefficient: 0.94, 0.90). The lowest reliability was found for the pubic arch and right- and left-sided levator-urethra gap (intraclass correlation coefficient: 0.13, 0.47, 0.49). By analysing the ultrasound data from the next 10 women, reliability improved for all levator hiatus measurements and the intraclass correlation coefficient ranged from 0.69 to 0.99. Only the intraclass correlation for the pubic arch remained below the level of good agreement (intraclass correlation coefficient 0.39) after the next 10 analysis.

In the interobserver study, excellent reliability for the entire procedure, including volume acquisition and offline analysis, between the two investigators for all levator hiatus measurements was shown (intraclass correlation coefficient range from 0.81 to 0.97). One exception was the measurement for the pubic arch (intraclass correlation coefficient: 0.67). There was no systematic bias between the two investigators.

Conclusion: Volume acquisition and offline analysis of levator hiatus dimensions using three- and four-dimensional transperineal ultrasonography can be learned with an acceptable level of effort. The intraclass correlation coefficients of the interobserver reliability study show that the technique is a reliable tool for examining the levator hiatus.

5.2 Paper II

231 nulliparous women were examined at mean gestational age of 36.8 (SD 0.7). 184 women (79.7%) had a normal vaginal delivery and 47 (20.3%) had an instrumental delivery (38 vacuum, two forceps, two vacuum and forceps and five caesarean section after full cervical dilatation). Indications for instrumental intervention were failure to progress (n = 27), fetal distress (n = 18), abnormal fetal presentation (n = 1), and exhausted mother (n = 1).

In both groups, women with normal vaginal delivery and women with instrumental delivery, no correlation between levator hiatus dimensions and the length of the passive second stage of labour was found.

For women with normal vaginal delivery, there was a weak inverse correlation between the length of active second stage of labour and both the anteroposterior diameter and levator hiatus area at rest (Spearman correlation coefficient, -0.23 and -0.29, $p<0.005$). Furthermore, there was a weak to moderate inverse correlation between the length of second stage and all levator hiatus dimensions during contraction (Spearman correlation coefficient, -0.21 to -0.35, $p<0.05$) in women with normal vaginal delivery. In deliveries with instrumental intervention, no significant correlation between levator hiatus dimensions and length of active second stage was found.

Women having normal vaginal deliveries had a significantly larger transverse diameter of levator hiatus at rest, during contraction, and during the Valsalva manoeuvre compared to women who required instrumental interventions (mean difference 0.29 cm (95% CI 0.16/ 0.41), 0.33 cm (95% CI 0.21/ 0.44) and 0.24 cm (95% CI 0.06/ 0.42)). The same was true for levator hiatus area at rest and during contraction (mean difference 1.22 cm^2 (95% CI 0.37/ 2.07) and 0.84 cm^2 (95% CI 0.22/1.46)). The results remained significant after adjustment for pre-pregnancy body mass index, fetal birth weight, total duration of second stage, gestational length, epidural analgesia, labour augmentation and levator ani muscle co-contraction during the Valsalva manoeuvre.

Conclusion: Larger levator hiatus dimensions at gestational week 37 at rest and during pelvic floor muscle contraction were associated with a shorter active second stage of labour and normal vaginal delivery.

5.3 Paper III

234 nulliparous women were examined at a mean gestational age of 20.9 weeks (SD 1.4 weeks) and again at 36.8 weeks (SD 0.7) of gestation. Major levator ani muscle defects were diagnosed in 44 women (18.8 % of all deliveries) at six weeks postpartum. 27 major levator ani muscle defects were diagnosed in 187 women with normal vaginal delivery (14.4%), 15 major levator ani muscle defects were diagnosed in 38 women with vacuum delivery (39.5%) and two defects were diagnosed in four women with vacuum/forceps or forceps delivery (50%). No major levator ani muscle defects were diagnosed antepartum or in the five women with second-stage caesarean section.

Women with major levator ani muscle defects had a significantly smaller levator hiatus area at rest and during the Valsalva manoeuvre when compared to women without defects. At 21 weeks of gestation the mean differences were respectively 1.03 cm^2 (95% CI 0.31/1.76) and 2.92 cm^2 (95% CI 1.77/4.07), and at 37 weeks of gestation 1.47 cm^2 (95% CI 0.62/2.32) and 2.84 cm^2 (95% CI 0.88/4.80).

Women with major levator ani muscle defects also had significantly less stretching of the levator ani muscle during Valsalva manoeuvre at 21 weeks of gestation (mean difference 7.46% (95% CI 3.0/ 11.91)) and less shortening of the levator ani muscle during contraction at 37 weeks of gestation (mean difference 3.45% (95% CI 0.71/ 6.18)). With the exception of stretching of the levator ani muscle, the results were confirmed in the logistic regression analysis, when adjustment was made for fetal birth weight, duration of first and second stage of labour, delivery mode and co-contraction of the levator ani muscle during the Valsalva manoeuvre.

Conclusion: A smaller levator hiatus area at rest and during the Valsalva manoeuvre in mid- and late pregnancy and less shortening of the levator ani muscle during contraction at 37 weeks of gestation were independently associated with major levator ani muscle defects occurring during delivery.

6 Discussion

6.1 Short summary

The volume acquisition and offline analysis of three- and four-dimensional ultrasound data of the levator hiatus can be learned in a short period of time. Both components of the ultrasound technique, the volume acquisition and the offline analysis were highly reliable. Larger levator hiatus dimensions in pregnancy were associated with a shorter active second stage of labour and normal vaginal delivery. Furthermore a smaller levator hiatus area and less shortening of the levator ani muscle during contraction antenatally were associated with major levator ani muscle defects.

6.2 Paper I

6.2.1 Strengths and limitations

Strengths of the study

The volume acquisition and the offline analysis followed a rigorous protocol. The investigators were blinded to each other's process of volume acquisition and offline analysis results.

The women included were randomly picked and are representative of the study population included in Paper II and III.

In the learning and interobserver reliability study we used the intraclass correlation, an appropriate statistical analysis for assessing reliability for continuous data [31, 36, 175-178]. In several papers Bland and Altman highlighted the advantages of using intraclass correlation and the 95% limits of agreement approach to assess reliability compared to other statistical methods for example Pearson correlation or logistic regression analysis [175, 179].

Furthermore, we investigated whether one investigator measured consistently larger values that the other investigator by one-sample t-test. This was done in order to explore systematic measurement bias between investigators, which is important information to report in this type of study [179]. With the exception of one previous inter-rater reliability study of levator hiatus dimensions [35] there is a lack of information about bias and the limits of agreement in the literature [29, 30, 32-34].

To our knowledge, our interobserver reliability study is the first study that assesses reliability of the entire ultrasound procedure, including volume acquisition and offline analysis. Previously published intra- and inter-rater reliability studies refer only to the process of offline analysis, since the measurements was carried out on previously stored datasets acquired by one single investigator [29, 30, 32-35]. By using stored datasets the source of variability in the measurements due to the process of volume acquisition was not taken into account [36].

Limitations of the study

A limitation of the learning study is that only one inexperienced investigator was included and the learning process therefore only represents the individual competence of this one investigator. Other inexperienced investigators might have presented different learning curves and intraclass correlation coefficients.

To evaluate the learning process for the volume acquisition, the inexperienced investigator analysed her own acquired volumes after she had confirmed acceptable intraclass correlation in offline analysis of volumes acquired by the experienced investigator (Figure 7; page 43). Therefore, the evaluation of the process of volume acquisition might be affected by further improvement in offline analysis skills.

No power calculation was performed. However, the number of 20 participants in the interobserver study is in line with similar previous reliability studies [29, 30, 33-35]. We had no *a priori* definition of which limits of agreement would be acceptable and related our limits of agreement to previously published reliability studies [35, 165].

Furthermore, using the same data for both the learning study and the interobserver reliability study can be discussed. Thus, the interobserver reliability for both volume acquisition and offline analysis might be affected by the learning process of the inexperienced investigator and we might have underestimated interobserver reliability for the entire ultrasound procedure.

The generalisability of our findings might be questioned due to the women's characteristics. In a group of women with pelvic organ prolapse, the volume acquisition might be more difficult to accomplish owing to the larger levator hiatus area during Valsalva manoeuvre and to the limited acquisition angle of the transducer [29]. On the other hand, 50% of our participants were examined six weeks postpartum, when anatomical structures displays low contrasted.

6.2.2 Interpretation

Learning study

The results of our learning study confirm the statement that "the volume acquisition can easily be learned but that the offline analysis might be more challenging" [38]. The process of learning the volume acquisition required only three hours, whereas the process of learning the offline analysis was more time consuming and required 20 hours.

Regarding the learning process of volume acquisition, it was apparently easier for the inexperienced investigator to instruct women to perform efficient pelvic floor muscle contractions than to perform proper Valsalva manoeuvres. One explanation could be that all participants had already been taught how to perform a correct pelvic floor muscle contraction by an experienced physiotherapist before the volume acquisition. In our study the Valsalva manoeuvre appeared more instructor-dependent. This result is in line with the findings by others, who showed that the quality of the Valsalva manoeuvre is influenced by the instructions given to the patients [64, 171]. The Valsalva manoeuvre might be embarrassing for women since involuntary passage of urine or wind may occur, and they might therefore not perform the manoeuvre properly. Another reason for an insufficient Valsalva manoeuvre is the co-contraction of the levator ani muscle, which results in smaller levator hiatus dimensions and is reported to be common in nulliparous women [64]. The Valsalva manoeuvre is used to assess pelvic organ mobility and an insufficient manoeuvre might lead to an incorrect evaluation of pelvic organ support [64]. It is therefore important that the investigator recognises an insufficient manoeuvre and helps the women to optimise their efforts.

Regarding the learning process of offline analysis, measuring the anteroposterior diameter and the levator hiatus area seemed to be relatively easy to learn, whereas measuring the pubic arch and the levator-urethra gap were more challenging to learn. For measuring the pubic arch and the levator-urethra gap, the investigator has to define the insertion of the levator ani muscle into the pubic bone. This might be difficult, especially when the muscle displays low contrasted and tissue demarcation appears poor.

A subsequent learning study for the process of offline analysis comfirmed our findings (180). One inexperienced investigator underwent an introduction procedure of 2.5 hours and analysed 50 volume datasets of nulliparous women at 12 weeks of gestation (180). The highest intraclass correlation between the inexperienced and the experienced investigator was also achieved for the anteroposterior diameter and the levator hiatus area (180). However, significant bias in 4 out of 9 measurements was found (180). Similar to us, they found that high reliability for the levator-urethra gap was harder to accomplish (180). A recent study investigated the learning process of the offline analysis involving 20 investigators with varying background and experience of ultrasound imaging from 11 different countries (181). After an average of 6 days in training the intraclass correlation ranged from 0.7 to 0.99 for the measurement of levator hiatus area during the Valsalva manoeuvre (181).

Interobserver reliability study

Several studies have reported intra- and inter-rater reliability data for the process of offline analysis in samples of both young nulliparous women, urogynaecological patients and recently, in women during the first pregnancy and in the postpartum period (29, 30, 33-35, 165, 180). Intraclass correlation coefficients between 0.5 and 0.96 for the levator hiatus dimensions have been shown (29, 30, 33-35, 165, 180).

Both, volume acquisition and offline analysis for two investigators were included in our study and an intraclass correlation above 0.81 for all levator hiatus dimensions with the exception of pubic arch was found. There was no systematic bias. Our limits of agreement are comparable with studies including nulliparous healthy volunteers (35) and urogynaecological participants (165) that had presented limits of agreement before us and a later study which evaluated inter-rater reliability in the postpartum periode (180).

An inter-rater reliability study published in 2014, in which 2 physiotherapists performed the volume acquisition and offline analysis separately on 14 healthy volunteers, confirmed high intraclass correlation for levator hiatus dimensions found by us (182). Further, no significant bias was found and the limits of agreement were comparable with ours (182). In a recent test-retest reliability study, women with pelvic organ prolaps underwent volume aquisition twice with an average time interval of 73 days (183). An intraclass correlation of 0.93 for levator hiatus area during Valsalva manoeuvre without significant bias was shown (183).

Many inter-rater reliability studies on measurements of the levator hiatus (33-35, 180, 182, 183), including ours, present cut-off values for the intraclass correlation from guidelines designed for other correlation estimates, for example Pearson correlation or kappa values (36). Such cut-off values can be discussed (36). Some authors recommend that an intraclass correlation above 0.75 is acceptable, while others recommend higher cuff-off values for ultrasound measurements (31, 36). In clinical practice, the degree of error that is acceptable between investigators depends on the consequences of the measurements (177, 179). We found the intraclass correlation above 0.8 in combination with our 95% limits of agreement and the absence of significant bias acceptable for our purpose.

6.2.3 Clinical implications

To implement a new examination technique in clinical practice the procedure should be easy to learn, reliable and valid. The latter has been shown in urogynaecological populations in several studies [7, 94, 161]. The results of our learning study show that the volume acquisition and the offline analysis of the levator hiatus can be learned in a short period of time and that the entire ultrasound procedure is a highly reliable. Even if normative data of levator hiatus dimensions is missing in the general population, our data suggest that three- and four-dimensional transperineal ultrasound of the levator hiatus could be incorporated into examinations of the pelvic floor, in the same way in which ultrasound of the uterus and adnexa is currently included in routine gynaecological examinations.

6.3 Paper II and III

6.3.1 Strengths and limitations

Strengths of the studies

The strengths of the studies were the relatively large sample size, the fact that few study participants were lost to follow-up and the minimal variation in gestational length and postpartum follow-up at the three ultrasound examinations.

Great care was taken to ensure the correctness of the delivery data obtained from clinical records. In a random subset, in outliers in the length of second stage of labour and in all cases of instrumental delivery, all clinical entries were reviewed to confirm the accuracy of the partogram data.

Volume acquisition and offline analysis of the ultrasound data followed a standardised protocol. Great care was taken to assess optimal pelvic floor muscle contraction and effective Valsalva manoeuvres. Reliability of the ultrasound measurements were tested amongst the four investigators and found to be acceptable. Render mode was used to measure levator hiatus dimensions, which may be regarded as providing a more representative image of the non-Euclidean shape of the levator ani muscle than measurements on a flat plane [159, 160, 184], which had been used in earlier studies [12, 28].

We have not excluded women with second-stage caesarean sections in any of the studies. Computer model studies simulating childbirth indicate that the fetal head contacts the levator ani muscle after it has descended one cm below the ischial spines [11, 133]. In our dataset, all five women with second-stage caesarean delivery had pushed actively for at least several minutes; two of them also underwent attempts at instrumental vaginal delivery (failed forceps), and the fetal head had clearly passed the ischial spines. The influence of the levator ani muscle on the delivery process in women with second-stage caesarean section is therefore highly likely (Paper II). Consequently the levator ani muscle in women with caesarean section has probably been exposed to substantial mechanical forces and stretching (Paper III).

The investigators were blinded to the women’s demographic data, previous ultrasound measurements and obstetric history. At the postpartum appointment, the women’s abdomens were covered by sheets and they were asked not to divulge any information regarding their deliveries (Paper III).

Having access to data such as age, pre-pregnancy body mass index, fetal birth weight and delivery mode for the total population made it possible to conclude that the study population was comparable with the total population of pregnant nulliparous women scheduled to deliver at Akershus University Hospital during the inclusion period (n= 2547).

Logistic regression analysis was performed to control for factors influencing the outcome measurements. To our knowledge, this was not done in previous studies assessing associations between antenatal levator hiatus dimensions and subsequent delivery outcome or major levator ani muscle defects.

Limitations of the studies

One possible limitation of the studies is that no *a priori* power calculation was performed. Nevertheless, we consider that power was not an issue in our studies, since we found clear, statistically significant differences between groups.

We might have underestimated the length of the passive second stage and thereby the length of the total second stage. Since the determination of full cervical dilatation depends on the time at which the midwife assesses the cervix, it is possible that full cervical dilatation has been present some minutes before vaginal palpation. This might be particularly true in uncomplicated deliveries when the midwife palpates less frequently or fails to capture changes in cervical dilatation due to a rapid delivery progress.

The estimation of the percentage change in levator ani muscle-length during contraction and Valsalva manoeuvre relative to resting length to assess the functional aspects of the muscle can be discussed (Paper III). To date, the association of the relative change in muscle-length determined with ultrasonography and other objective measurement of levator ani muscle function, especially in pregnancy has been poorly studied [(185)]. Van Delft et al. [(185)] provided data on percentage reduction in the levator hiatus area from rest to contraction during pregnancy and found a significant moderate correlation with digital assessment of muscle function. In urogynaecological populations moderate correlation between percentage decrease in muscle-length during contraction and digital palpation was found [(165, 186)]. Recently, correlation coefficients of 0.6 and 0.7 between the percentage decrease in levator hiatus area during contraction and manometry data and digital palpation, respectively, on 559 women recruited from a normal Norwegian population was shown [(187)]. To our knowledge there is no data published which demonstrates the association between the percentage increase in muscle-length during Valsalva manoeuvre during pregnancy and other clinical findings.

The generalisability of our studies can be discussed. One inclusion criteria was the ability to understand a Scandinavian language. Therefore, our study population represented mainly Caucasian women and the results might be specific to this ethnic group. Significant differences in levator hiatus dimensions and levator ani muscle morphology in Caucasian women compared to African and Asian women have been shown using magnetic resonance imaging and transperineal ultrasound (188-190). However, compared to our study population, a Chinese study (191) including 405 pregnant nulliparous women found only marginally smaller levator hiatus dimensions in the third trimester than we found (169). In fact, studies performed in Australia and the Netherlands reported larger levator hiatus dimension in third trimester (100, 192), whereas two other studies on mainly Caucasian women found levator hiatus dimensions in late pregnancy that were similar to our findings (193, 194).

Furthermore, there are differences in obstetrical practice between both countries and individual hospitals reflected in the different rates of instrumental vaginal deliveries and caesarean sections reported. This also applies to the management of the second stage of labour and choice of forceps or vacuum to shorten the last part of the delivery.

6.3.2 Interpretation

Interpretation Paper II

We found no correlation between levator hiatus dimensions and the passive second stage in women with and without instrumental intervention during delivery. This is not surprising, as computer models showed that it is in the latter stage of labour that the fetal head increasingly interacts and stretches the levator ani muscle [11, 133, 195].

Regarding active second stage of labour, the clearest association was found between a larger anteroposterior diameter and levator hiatus area both at rest and during contraction at 37 weeks of gestation and a shorter duration of active second stage of labour in women with normal vaginal delivery. There was an absence of an association between levator hiatus dimensions during the Valsalva manoeuvre and the length of active second stage. Our findings are in line with the results of a previous study on 41 women with vaginal deliveries, examined with three- and four-dimensional transperineal ultrasound in late pregnancy [12].

The fact that we did not find an association between the length of active second stage in the women with instrumental intervention during delivery might be explained by the iatrogenic shortening of the delivery duration in this group.

Regarding delivery mode, the most marked finding in our study was the association between a larger transverse diameter at rest and during contraction in women with normal vaginal deliveries compared with women to required instrumental intervention during delivery.

The association between antenatal levator hiatus dimensions and subsequent delivery mode has been previously reported in two studies [12, 13]. Using transvaginal ultrasonography larger levator hiatus area during the Valsalva manoeuvre antenatally was found in women who were delivered vaginally compared to women delivered by caesarean section [13]. Dietz and Lanzarone's [12] findings were similar to ours. They also found a larger transverse diameter during contraction antenatally in women with subsequent normal vaginal delivery compared to women with instrumental delivery [12]. Recently, van Veelen et al. confirmed this finding [196].

Using transperineal ultrasonography, the transverse diameter of the levator hiatus is measured as the widest part of the levator hiatus, perpendicular to the anteroposterior diameter [29, 33, 35]. Both at rest and during contraction, this is normally where the levator ani muscle inserts into the pelvic bone and represents the least flexible part of the muscle. A larger transverse diameter might represent a more lateral insertion of the muscles into the pelvic bone and, from an obstetrical perspective, could indicate a more suitable pelvic outlet. There is evidence that the dimensions of the bony pelvis also influence the birth process [5, 197, 198]. Nevertheless, to date, dimensions of the bony pelvis, as estimated by pelvimetry or transperineal ultrasound, cannot be used to predict labour outcome [199, 200]. Therefore, the combined musculoskeletal configuration of the pelvis might be of importance to the birth process.

Surprisingly, at 37 weeks of gestation, we did not find an association between the size of the levator hiatus area during the Valsalva manoeuvre and delivery mode. One possible explanation could be that the area achieved during voluntary Valsalva manoeuvre does not represent the potential of the muscle to distend under extreme force. In late pregnancy the mean levator hiatus area during the Valsalva manoeuvre was 18.0 cm^2, which is comparatively small to the cross-sectional area of approximately 70-90 cm^2 that is required when the fetal head is delivered [(12)].

In our analysis, there were two reasons why we did not stratify for indication of operative delivery. Firstly, several of the instrumental deliveries were carried out on the combined indication of fetal distress and failure to progress. Secondly, the role of the levator ani muscle in the risk of fetal distress is not yet clear. It has been postulated that poor pelvic muscle compliance might increase intrauterine pressure and promote fetal distress [(12)]. Performing a subanalysis on indication for instrumental delivery (fetal distress and failure to progress) in our population did not change the results. In a recent study, stratification by the two indications for instrumental intervention during delivery was performed [(196)]. No statistically significant differences in antenatal levator hiatus dimensions between the two strata was found [(196)]. These findings support the hypothesis that the levator hiatus dimensions can predispose for fetal distress and/or that an unambiguous allocation of the indications, fetal distress or failure to progress, is not possible.

Interpretation Paper III

We found that women who were diagnosed with major levator ani muscle defects six weeks postpartum had a significantly smaller levator hiatus area at rest and during the Valsalva manoeuvre at 21 and 37 weeks of gestation and less shortening of the levator ani muscle during pelvic floor muscle contraction at 37 weeks of gestation than women without defects.

To our knowledge, few studies have evaluated the association between levator hiatus dimensions during pregnancy and levator ani muscle defects occurring during delivery [(28, 201, 202)]. Only one of them has adjusted for instrumental intervention during vaginal delivery as a confounding factor [202]. Shek at al. [28] found no significant differences in levator hiatus area at 37 weeks of gestation in women with and without major levator ani muscle defects diagnosed 4 months postpartum. Neither did a more current study [201]. However, in the latter study a significantly shorter anteroposterior diameter in women with major levator ani muscle defects postpartum compared to women without defects was found [201]. Recently, our finding of the association between a smaller levator hiatus area in late pregnancy and major levator ani muscle defects was confirmed by a Chinese-study [202]. They also found a significantly shorter anteroposterior diameter in women with major levator ani muscle defects compared to women without defects [202].

The association between a smaller levator hiatus area antepartum and a higher risk of levator ani muscle defects occurring during delivery is plausible. Svabik et al. [10] estimated that the strain required for vaginal delivery on top of the distension obtained at rest and during maximal voluntary Valsalva manoeuvre varied between women by a factor of 4.5 and 10 respectively. Therefore, in women with a smaller levator hiatus area at rest and the during Valsalva manoeuvre in late pregnancy the muscle fibres stretch much more to allow for the passage of the fetus. A current study evaluated the bony pelvic dimensions in women with and without major levator ani muscle defects [203]. A significantly shorter anteroposterior bony pelvic dimension in women with major levator ani muscle defects was found and the authors hypothesise an association between a smaller bony pelvis and a shorter levator ani muscle [203]. A shorter levator ani muscle must stretch more during delivery and might therefore be at higher risk of muscle defects [203].

The physiological demands on the levator ani muscle function are contradictory. For providing continence and pelvic organ support the levator ani muscle’s ability to decrease muscle-length during contraction might be of relevance (165, 168). Whereas during childbirth the muscle's ability to stretch might be of importance in regard to preventing major levator ani muscle defects (165).

In our study, at 21 weeks of gestation, the percentage decrease in muscle-length during contraction relative to resting state did not differ in women with and without major levator ani muscle defects. However, at 37 weeks of gestation, women with subsequent major levator ani muscle defects had a significantly less percentage decrease in muscle length during contraction relative to resting state than women without such defects. At 21 weeks of gestation, women in the defect group had significantly less increase in muscle-length during the Valsalva manoeuvre relative to their resting state than women in the non-defect group. However, when controlling for possible confounding factors, the effect of muscle stretch on the occurrence of major levator ani muscle defects was only marginal. In late pregnancy, muscle stretch did not differ between women with and without subsequent major levator ani muscle defects. The results are influenced by the fact that the levator hiatus area at rest increased less from gestational week 21 to 37 in the defect group compared to the non-defect group. However, during contraction and Valsalva manoeuvre the levator hiatus area increased equally during pregnancy in both groups. The missing significance in muscle stretch and the emergence of significance in muscle-length decrease during contraction at 37 weeks of gestation is therefore a result of the pregnancy-related change in the levator hiatus during rest.

Several longitudinal studies showed a marked increase in levator hiatus dimensions during pregnancy (169, 191-193). It is assumed that this increase prepares the woman's pelvic floor for delivery and minimises the risk of childbirth-related injuries (101-103, 193). Our data supports this hypothesis, since women in the defect group had less of an increment in levator hiatus area at rest from 21 to 37 weeks of gestation than the women in the non-defect group.

6.3.3 Clinical implications

In modern obstetrical care, patient satisfaction with the birth process and quality of life postpartum are of great importance (16, 145). Associations between prolonged second stage and instrumental intervention during delivery and both fetal complications as well as maternal somatic and psychological trauma have been shown (14, 115, 116, 122, 124, 204-206).

Regarding the woman's pelvic floor, childbirth has been cited as one of the important risk factors for female pelvic floor dysfunction (23, 79, 207). However, not all parous women will develop pelvic floor dysfunction later in life (20, 76, 207) and it might not be the fact of having undergone a vaginal childbirth per se but the pelvic floor injuries which occur that increase the risk of subsequent pelvic floor dysfunction (21).

Attempts have been made to develop models which include antenatal ultrasonographic data from the levator ani muscle to predict uncomplicated deliveries (17, 193) and major levator ani muscle defects occurring during delivery (28, 208). However, to date, no model has been implemented in routine clinical use.

Our data suggests an association between less percentage decrease in levator ani muscle-length during contraction at 37 weeks of gestation and major levator ani muscle defects occurring during delivery. A randomised controlled trial from Norway on pelvic floor muscle training during pregnancy showed a significantly shorter second stage of labour in women who underwent pelvic floor muscle training than in the women in the control group [209]. Those findings suggest that pelvic floor muscle training might improve the ability of levator ani muscle to facilitate delivery and to resist major levator ani muscle defects. It has been a concern that increased pelvic floor muscle strength may increase the length of the second stage of labour [210]. Several studies have not found an association between pelvic floor muscles strength in pregnancy and the length of the second stage of labour [210, 211] or a negative effect of pelvic floor muscle training during pregnancy on the delivery process [212, 213].

We found an association between smaller levator hiatus area at rest and during Valsalva manoeuvre antenatally and major levator and muscle defects postpartum. Increasing the levator hiatus area at rest and during Valsalva manoeuvre during pregnancy might be difficult. A randomised controlled trial tested whether short-term vaginal dilatation with a vaginal balloon in late pregnancy reduces the risk of major levator ani muscle defects [214]. No statistical differences in muscle defects between the intervention and the control group were found. However, no information as to whether the vaginal dilatation changed the levator hiatus area at rest and during the Valsalva manoeuvre during pregnancy was obtained in the study.

Childbirth is a highly complex process and the levator ani muscle is only one factor influencing events. In the present studies, there were remarkable inter-individual variations in the size of the levator hiatus. Furthermore, the differences in levator hiatus dimensions between both delivery groups and women with and without muscle defects were measured in millimetres. To date, cut-off values for a “birth-suitable” levator hiatus are not available.

However, the findings of our studies contribute to our understanding of the mechanisms behind the birth and delivery process.

7 Conclusion

We have shown that the three- and four-dimensional transperineal ultrasound procedure for assessing the levator hiatus is easy to learn and reliable. The intraclass correlation for the entire procedure, both the volume acquisition and the offline analysis were above 0.81 for all levator hiatus dimensions in the axial plane except for the pubic arch (intraclass correlation 0.67) for two independent investigators. Levator hiatus dimensions assessed by three- and four-dimensional transperineal ultrasound at mid- and late pregnancy in nulliparous women were associated with both the process of labour and major levator ani muscle defects. Larger levator hiatus dimensions at rest and during pelvic floor muscle contraction in late pregnancy were associated with a shorter active second stage of labor and normal vaginal delivery. Smaller levator hiatus area at rest and during the Valsalva manoeuvre in mid- and late pregnancy and less shortening of the levator ani muscle during contraction at 37 weeks of gestation were associated with major levator ani muscle defects occurring during delivery.

8 Further research

To be able to compare levator hiatus measurements from different centres, reliability of the measurements should be ensured by multicentre reliability studies. Recently, several studies have confirmed our findings on the learning process and the interobserver reliability of levator hiatus assessment using three- and four-dimensional ultrasonography in different populations [29, 30, 33-35, 165, 180, 182]. However, even if referring to the same methodology, there are differences in levator hiatus dimensions in comparable study populations (nulliparous pregnant women) indicating that there must be distinct differences in volume acquisition and offline analysis.

To evaluate the impact of pregnancy on levator hiatus dimensions, levator hiatus dimensions should ideally be assessed before conception. There is a need for longitudinal studies which examine women already prior to pregnancy and follow them through pregnancy. It is likely that the marked changes of the woman's pelvic floor during pregnancy occur in order to prepare for delivery [101-103, 193]. To date, the role of pregnancy-related changes of the levator hiatus dimensions and the functional aspects of the levator ani muscle for both the delivery process and the risk of childbirth related injuries has been poorly studied. Being one of the few research groups with ultrasound data at two time points during pregnancy, we hope to investigate this research question in the near future.

Attempts should be made to influence the levator hiatus dimensions and the functional aspects of the levator ani muscle during pregnancy. This might increase the levator ani muscles ability to facilitate delivery and decrease the risk of childbirth-related injuries. For example, pelvic floor muscle training may improve muscle control and both strengthen the muscles and enhance the ability to relax, which might influence the process of labour positively [209]. The effect of pelvic floor muscle training on levator hiatus dimensions and on the decrease in muscle-length during contraction relative to resting length during pregnancy has not yet been studied. Randomised controlled trials comparing levator hiatus dimensions in women performing pelvic floor muscle training during pregnancy with non-exercising women using three- and four-dimensional transperineal ultrasound are needed. The same is true for the effect of pelvic floor muscle training during pregnancy on childbirth-related pelvic floor injuries, especially on major levator ani muscle defects.

Larger levator hiatus dimensions might indeed be suitable for delivery. However, an association between larger levator hiatus dimensions and pelvic organ prolapse in urogynaecological populations has been shown [7, 94, 161]. Often, pelvic floor dysfunction ocures decades after delivery [21, 215] and many women present symptoms of pelvic floor dysfunction without any detectable pelvic floor injuries [6]. There is a need for longitudinal studies which follow women before and through pregnancy, in the postpartum period, but also in a long-term follow-up beyond the menopause to explore the association between levator hiatus dimensions earlier in life, for example before and during pregnancy and pelvic floor dysfunction later in life.

9 References

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Appendix

Appendix

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