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Anatomy and Neurophysiology of the Lower Urinary Tract and Pelvic Floor

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1.1 Bladder

The urinary tract undergoes a very dynamic development during foetal life. Emerging from the metanephros, the human kidney begins to produce urine at 10–12 weeks of gestation [1, 2]. At this time the bladder is a cylindrical tube of cuboidal cells in a single layer. During the second trimester, 4–5 cell layers develop, forming a low compliant 'bladder' at the 21st week of gestation [3–5]. The foetal bladder handles a relatively large amount of fluid, draining to the amniotic cavity with a subsequent oral reuptake by the foetus. The salt and water homeostasis, however, is cleared by the placenta and eventually by the mother's kidneys [6]. Any deviation from this cycle may lead to a more or less pathological consequence for the foetus. In the beginning the lower urinary tract is a conduit with coordinated peristalsis propulsing the urine through the urethra, as is the case with the upper urinary tract. After the formation of the external sphincter, the lower urinary tract develops graduate filling and emptying, and the bladder wall properties change. From being a coordinated peristaltic conduit, the bladder becomes an organ with chaotic micromotions in the bladder wall.

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1.2 Urethra, Sphincter and Pelvic Floor

The external rhabdosphincter is crucial for continence. In male foetuses a common sphincter urethrae primordium can be found already at the ninth week of gestation. However, the final horseshoe-shaped rhabdosphincter is not seen until late in gestation [7–9]. Its musculature primarily consists of type-1 slow twitch fibres as a marked contrast to the rest of the pelvic floor which predominantly is type-2 fast-twitch fibres. Together with the external anal sphincter and the ischiocavernosus and bulbocavernosus muscles, the urethral sphincter has been shown to be controlled from the Onuf's nucleus at level S1–S2, situated in the front horn as two separate densities, one innervating the external urethral sphincter and ischiocavernosus and the other one the external anal sphincter and bulbocavernosus. This nucleus has a very high density of serotonin and norepinephrine receptors.

The external striated sphincter not only deviates in muscular characteristics from the surrounding pelvic floor; it is also, from an investigational and diagnostic point of view, difficult to monitor. It is mainly lying in front of the urethra, almost as a horseshoe. Therefore, when it is claimed that sphincter electromyography has been obtained, it is usually a misinterpretation. One has to settle with monitoring pelvic floor activity which gives a far more lenient investigational situation because one can use perianal surface electrodes instead of the more invasive needle electrodes.

The rest of the pelvic floor, which as mentioned consists of musculature with fast-twitch fibres, supports the urethra and acts as a guarding reflex elicitor and resistance in increased musculature during coughing and Valsalva.

The innervation and the properties of the external sphincter may, in the future, have significant clinical importance since it has been shown that OAB symptoms can be elicited through lack of stability of the urethra.

1.3 Voiding

Knowledge pertaining to the normal development of voiding function is crucial to the understanding of normal voiding and distinguishing it from abnormal voiding function. Evolution of voiding function begins in the first trimester of pregnancy and continues throughout childhood and adolescence [10–17]. Major developments are apparent such as the development of continence; others are more subtle. The simultaneous development of the neurogenic voiding reflex pathway has been shown as early as the 17th week of gestation by immunohistochemistry of autonomic innervated detrusor muscle bundles, while the adrenergic nerve supply was not seen before the 30th week of gestation [18]. In 1995 Yeung et al. showed that voiding in the neonatal period was not a mere autonomic reflex but also involved immature cortical mechanisms [19].

The voiding frequency undergoes a very dynamic development from foetal life to adolescence.

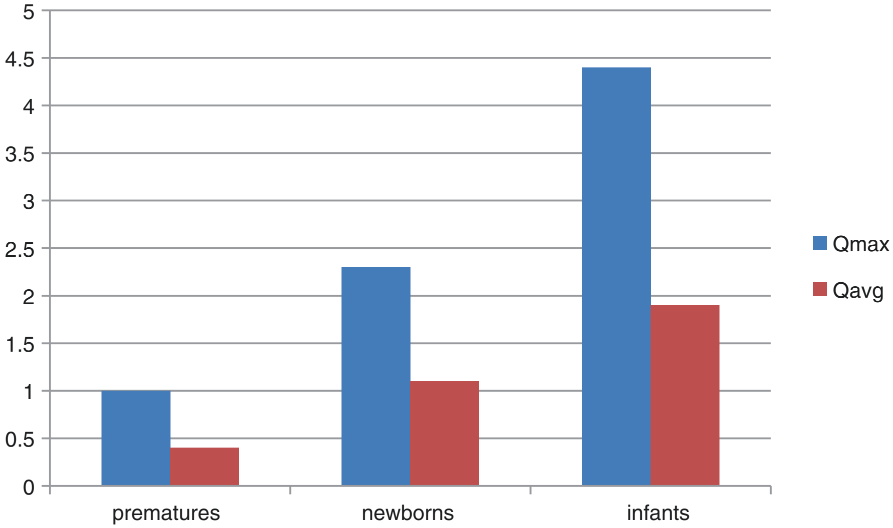

Fig. 1.1 Development of average (Q_{avg}) and maximum (Q_{max}) (mL/sec) flow rate with time

In the last trimester, there is a frequent rhythmic filling and emptying of the bladder at a rate of up to 30 sequences per 24 h.

During infancy the voiding frequency decreases to approximately one third with a further decrease towards stability from age 7, where more than seven voidings a day and less than three are considered abnormal. Conversely the flow rate increases with age (Fig. 1.1).

A normal voiding is described as a bell-shaped flow curve leading to a complete emptying of the bladder. The physiologic background consists of a relaxation of the bladder neck elicited via NO release, an introduction of urine into the proximal part of the urethra causing stimulation of mechano- and chemoreceptors, leading to stimulation of a detrusor contraction which overcomes the resistance of the external sphincter, and then the voiding is in progress. This pattern is considered to be the normal, but voidings both in children and in normal adult volunteers have been shown to be far more versatile, with several configurations including the bell shaped. Schmidt et al. showed that voiding shows a rather low degree of consistency in normal young men [20]. Lu et al. have confirmed the same both using natural fill overnight ambulatory urodynamics and artificial filling conventional urodynamics in children with OAB [21]. In the early stages of postnatal life into infancy and childhood, several interesting observations have been made. Flow curves with plateau shaped can be seen in prematures and newborns, while the spike-dome configuration is displayed in newborns and infants [22–24]. These patterns seem to be transient, while staccato and interrupted flow continues to occur in older children. The predominant flow curve shape in kindergarten and school children seems to be the bell and tower pattern [12, 14, 25, 26]. However, Bower et al. found in flow studies of 96 healthy 5–14-year-old children staccato-shaped flow curves in 30% of all initial voids [17]. They describe this surprising finding which is not in accordance with other studies, but had no plausible explanation [12, 14, 25]. Mattsson et al. showed that the number of staccato or interrupted voidings, seen in 16% of the children during an initial voiding, decreased to less than 3% in the subsequent voiding, while this fraction was stable in the observations of Bower et al. who recorded on average 4.4 micturitions per child [17, 27].

Consequently normality and abnormality of voiding seem far from fully elucidated.

1.4 Bladder Capacity

Estimating bladder capacity in children is not only relevant when determining whether or not the voided volume is within normal range but also when evaluating the need for, and frequency of, intermittent catheterization. In the investigative setting, the estimated volume is used to decide the amount of contrast used for MCUG. Bladder capacity obviously varies depending on age and weight of the child, but also depending on the filling media, the rate of filling and the presence of a urethral or suprapubic catheter.

The bladder has a paradox reaction to filling. The faster it is filled, the more it can accommodate [28], a factor which has to be taken into consideration when urodynamics are to be analysed. The relationship between filling and volume is even more complicated since it seems as if the change in filling rate results in even more volume changes during the day having a maximum during night.

Following these variations there are different measures of bladder capacity, according to the situation. The expected maximum voided volume, being the term for capacity recommended by the ICCS [29, 30], can be calculated by the following formula: *Estimated bladder capacity = 30 mL* × *(age + 1)*, which is a modification from the original formula (*Bladder capacity (ounces) = age + 2 years*), presented by Koff in 1983 [31] and later validated in other studies [32]. Several alternative formulas have been proposed, most of them based on cystometric data. Fairhurst et al. proposed two formulas based on either L1–L3 distance on X-ray or weight (*Estimated bladder capacity (mL) = (7* × *weight in kg) + 1,2)* which offer a more accurate estimate in younger infants [33], an important supplement to Koff's version, which is applicable for children aged 4–12 years.

How to measure the actual bladder capacity in a relevant way can also be debated. When using the bladder diary, voided volumes and maximum voided volume (earlier referred to as functional bladder capacity) are obtained from a physiological setting with natural filling of the bladder. Alternative terms for bladder capacity are cystometric bladder capacity (recorded at first sensation) and maximum cystometric capacity (recorded when voiding commences), both obtained during urodynamic investigation, with a catheter in the bladder filling the bladder at a faster rate and with another medium, than under physiological conditions, inevitably affecting the measurements.

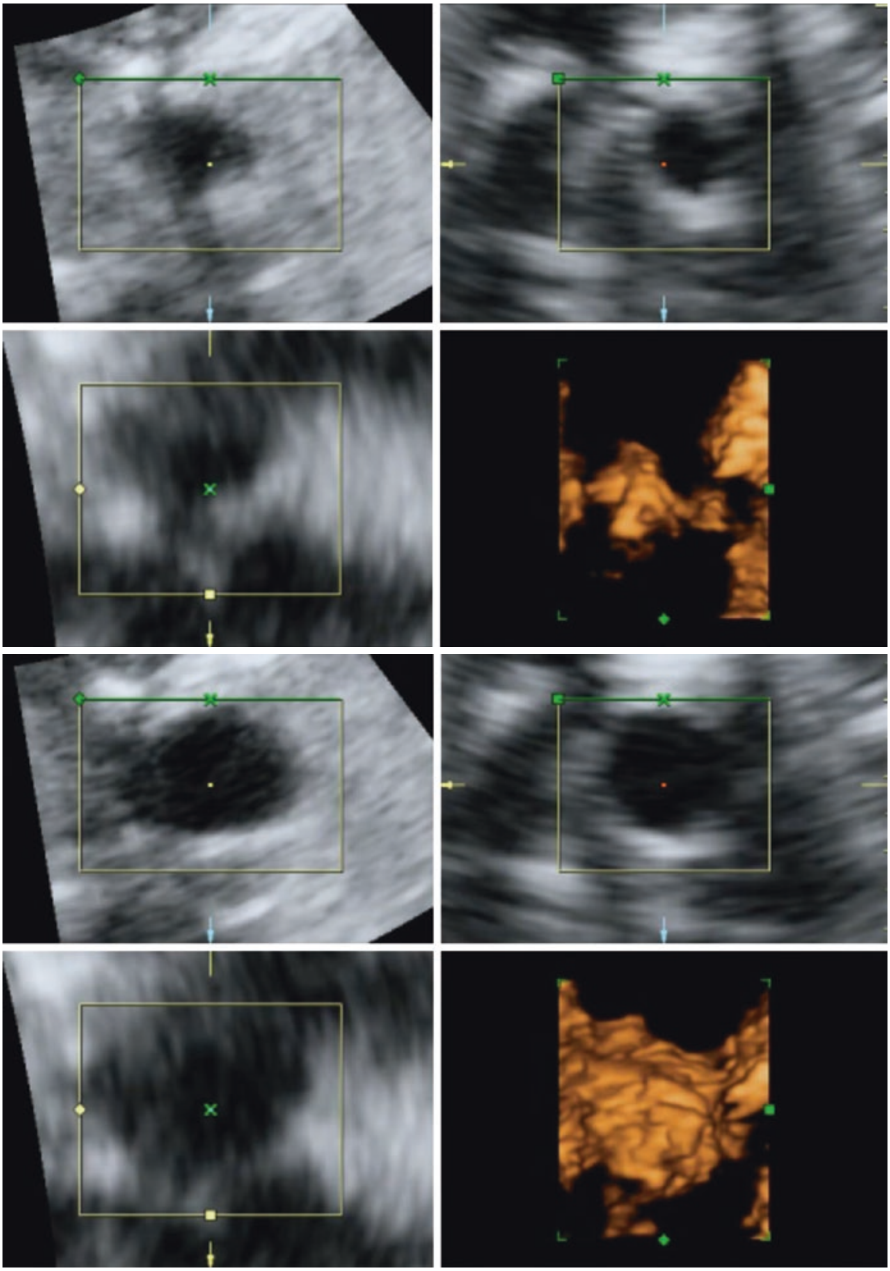

Fig. 1.2 Voiding in third trimester obtained by way of 3-D ultrasound. A bladder volume of appr. 4 mL is reduced to appr. 1 mL during the voiding

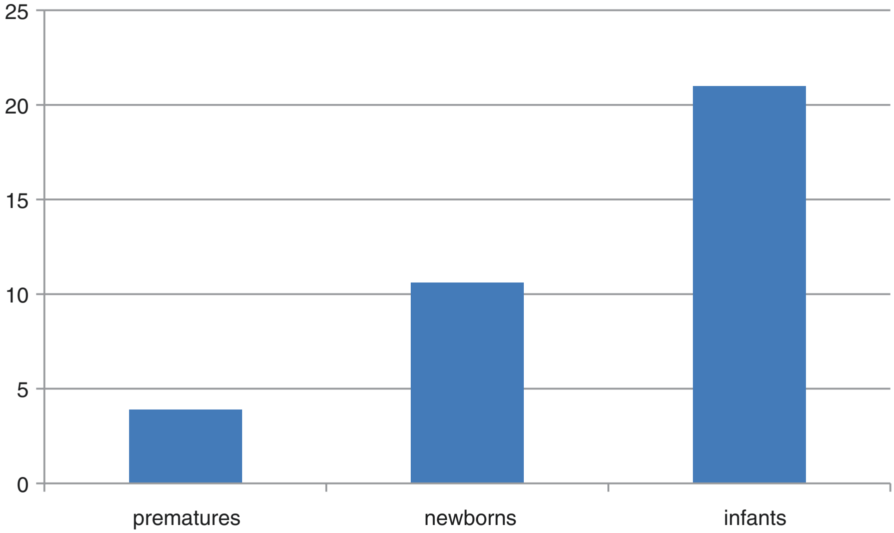

Fig. 1.3 Development of voided volume with age (mL (median)) assessed by transit-time ultrasound flow measurement [21–23]. The voided volume is smaller than the estimated bladder capacity indicating incomplete bladder emptying [10]

The 4-h observation period gives insight into both voided volume and post-void residual urine. While diapers are weighed after each voiding, the concomitant residual urine is assessed by transabdominal ultrasound [34]. The sum gives an estimate of bladder capacity. In prematures Sillen et al. found a bladder capacity of 12 mL at 32 weeks of gestation [35, 36]. Gladh et al. estimated the bladder capacity of 2 -week-old newborns to 48 mL, while Bachelard found a bladder capacity of only 20 mL in 3-month-old infants [13, 37]. Bachelard et al.'s subjects were the asymptomatic siblings of infants with vesicoureteral reflux studied by invasive cystometry. The indwelling urethral catheter may therefore well explain some of these discrepancies. A later study from the same institution reported a median bladder capacity of 52 mL at 8 months of age [38]. It is evident that the aforementioned studies report large inter- and intraindividual variation with regard to the bladder volume that initiates voiding, voided volume and post-void residual urine. The influence of frequent manipulation of diapers, ink indicators and transabdominal ultrasound in these studies has undoubtedly affected outcomes [39]. The ICCS definition of estimated bladder capacity (EBC), originally proposed by Hjälmås and Koff, seems therefore reasonable to go by in the clinical setting [29–31, 40]. However, it is worth remembering that prematures, newborns at term and infants void at varying degrees of EBC which again limits the value of an absolute EBC (Figs. 1.2 and 1.3). The voided volume does not seem to influence the flow curve pattern [24].

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