A Functional Anatomy of the Lower Urinary Tract in Children

Pelvic Anatomy III

Jeremy O.N. LAWSON

In 1967 Martin Barkin and I [3] studied the pelvic structures in 13 neonates. Seven of these we dissected in the fresh state and six were placed in preservative and decalcified before serial sections, seven μ thick, were cut and stained [3,42,43,44].
Herbert Eckstein took a very active interest in our findings. He was particularly interested in an explanation for the usual sites of obsruction in bladder neuropathy. These had been observed just below the bladder neck and in the membranous urethra. The abnormality did not appear to lie in the external urinary sphincters, as biopsies taken from these muscles showed that they had atrophied and pudendal neurectomy was proving ineffective.

The small rapid action nature of the striated muscle fibres in the voluntary sphincter made the striated sphincters an unlikely site of sustained muscle "spasm". I am basing my comments on the re-examination of our material and the examination of the serial sections of six further neonatal pelves [*].

This report aims to answer the following questions:

1. How does the normal bladder empty?

2. How does the urethra close rapidly and completely to create a urine proof closure?

3. How is this closure maintained, effortlessly over long periods?

4. How is micturition initiated, spontaneously and by voluntary effort, and completed?

5. How is the urethra emptied at the end of micturition?

In the male:

6. If the urethra opens to receive semen what prevents retrograde flow into the bladder?

7. How is the semen expelled from the posterior urethra during ejaculation without retrograde flow?

Though the structure and function of the lower urinary tract must be considered as a whole, for convenience, it subdivides on embryological, anatomical and physiological grounds. Indeed only one structure, the inner longitudinal muscle coat, is common to all the subdivisions.

As so many terms have been applied to these structures the basic subdivisons will be as follows:

1. The body of the bladder.

2. The base of the bladder and upper urethra.

3. The remaining urethra.

a) In the male this includes the prostatic and membranous urethra.

b) In the female, the whole urethra below the upper internal sphincter.

EMBRYOLOGY

It has been shown in the fetus [14,15], that the muscle found in the three zones, the detrusor of the body of the bladder, the smooth muscle loops of the bladder base and trigone, the muscle of the prostatic urethra and the smooth muscle system of the membranous urethra, develop separately.

1. The fundus or body of the bladder

It is widely accepted that the body of the bladder is derived from the allantoic bulb [1,69].

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[*] Pelvic Anatomy, Part I and II [44]

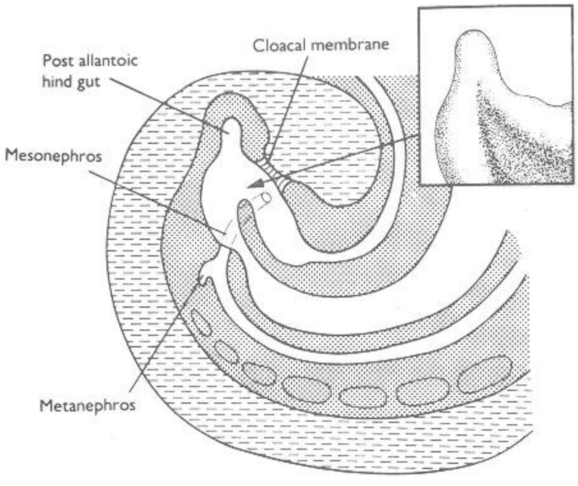


Figure 1. 5 week embryo (5-7.5 mm). The postallantoic hind gut has reached the surface, behind the body stalk, to form the cloacal membrane. Angulation of the cloacal dilatation has divided the dilatation into two. The mesonephros has grown down from the nephrogenic ridge to meet the anterior subdivision, which is in continuity with the allantoic bulb (In: Surgery of Anus, Rectum and Colon. Keighley and Williams. London, Saunders) (46).

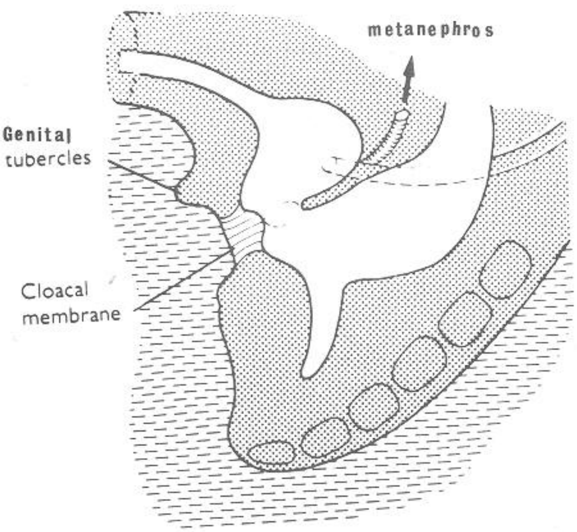


Figure 2. 6 week old embryo (8 mm). The genital tubercle has appeared in front of cloacal membrane. The large ventral cavity (urogenital sinus and allantoic bulb) and the small posterior (primitive rectum) are connected by the cloacal passage (In: Surgery of Anus, Rectum and Colon. Keighley and Williams. London, Saunders) (46).

2. Bladder base

The development of bladder base, the bladder neck and the upper urethra include structures derived from incorporation of the fused mesonephric or Wolffian ducts into the primitive cloaca or urogenital sinus (Fig. 1-4). From these structures derive the ureteric orifices, the trigonal structures and a strip down the back of the urethra. The urethral strip extends as far as the insertion of the trigonal muscle to the verumontanum, in the male, and down to the external urinary meatus, in the female.

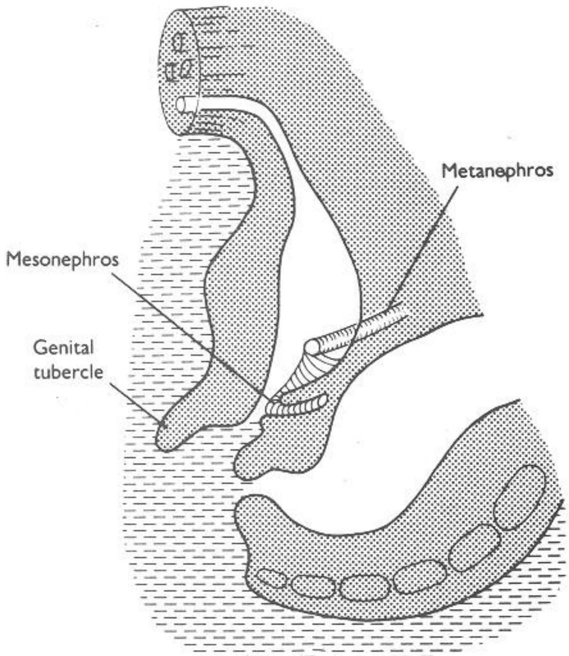


Figure 3. 6 week old embryo (10 mm). The genital tubercles are well developed. The incorporated mesonephric and the metanephric tubes are seen above the region of the cloacal membrane (In: Surgery of Anus, Rectum and Colon. Keighley and Williams. London, Saunders) (46).

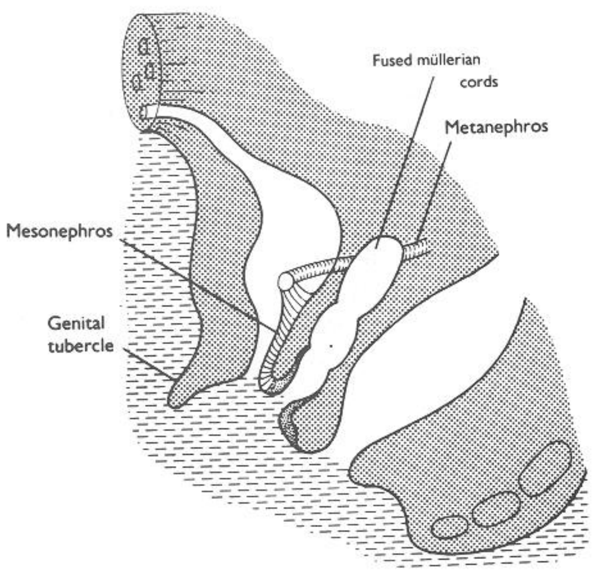


Figure 4. 7 week old female embryo (16 mm). The fused Müllerian cord is seen and its relationship to the mesonephric and metanephric tubes (In: Surgery of Anus, Rectum and Colon. Keighley and Williams. London, Saunders) (46).

The embryological derivation from mesonephros is suggested by congenital anomalies. In single ureter ectopia the structures derived from mesonephros are absent proximally. In urethral ectopia, and in some cases of absence of the whole pylon, an ipsilateral absence of the trigone may be associated with a corresponding defect in the bladder neck and urethra.

Muscular elements are first identifiable, round the *base of the* developing bladder, by the 110 mm stage. Loops of smooth muscle extend down in the wall of the upper quarter of the female urethra, the rings being completed dorsally by their insertion into an extension of trigonal tissue down the back of the urethra [14,15]. Longitudinal muscle is seen in the trigonal area, when the structure is fully developed at 200 mm C.R.L.. Extending down as far as the verumontanum, in the male, it covers two thirds of the posterior wall of the urethra in the female.

3. The posterior urethra in the male and the urethra in the female

The male posterior urethra and the female urethra appear to develop from the cloaca (urogenital sinus) and the dorsal strip of mesonephros (Fig. 1-4).

In the male the lobes of the prostate develop from epithelial buds, appearing as early as the twelfth week I.U.L. Six lobes develop: Four, the anterior, subcervical, right and left lateral, because they develop between the inner longitudinal and the circular smooth muscle layers, have been described as intraurethral. Two, the median and posterior, develop outside the smooth muscle coats and have been described as extra-urethral [34,48,49]. The anterior lobe subsequently atrophies. Only the duct for the posterior enters the urethra below the verumontanum, the remainder drain into the urethra between the veru and the bladder neck posteriorly. In fetal sections no prostatic tissue was seen ventral to the urethral lumen. Striated muscle, first noted in the 60 mm C.R.L. fetus, surrounds the circular smooth muscle layer from the bladder neck, cranially, to the pelvic floor, caudally [14,15].

In the neonatal sections the stratified cuboidal epithelium lining the urethra is identical to that seen in the "transitional zone" of the anal canal, suggesting a common cloacal embryological origin.

4. The membranous urethra in the male and the lower urethra in the female

In the male the lower urethra below the prostate develops in cloacal (urogenital sinus) structures but in the female it includes the posterior strip derived from mesonephros. Circular smooth muscle, which surrounds the infra montanal urethra and the membranous urethra in the male, appears to develop independently from the above of the prostatic urethra [11,14,15].

5. The supporting muscles and voluntary sphincters

The origin of the voluntary sphincters and levator ani is not clear. The antero-medial part of the levator ani, the pubovisceral muscles, is considered homologous with the "rectus column", from which the rectal muscles develop (Fig. 5). Absence of the upper part of the striated sphincter, in the "Absent Abdominal Wall Syndrome", suggests that this part of the sphincter has a similar origin. The "Horseshoe" shaped loops of striated muscle, surrounding the urethra as far as the bladder neck, are seen from the 100 mm stage [14]. In the female the lower part of the urethral sphincter also extends back round the vagina. In the male the compressor of the membranous urethra is present in cases of "Absent Abdominal Wall Syndrome". This suggests that the lower parts of the voluntary sphincter, may develop, with the deep anal sphincters, from epaxial rather than paraxial myotomes (Fig. 5).

ANATOMY

Mucosa

The bladder and urethra is lined with stratified cuboidal, uroepithelium. The trigonal area is richly supplied with mucus glands. Ducts from para urethral glands enter the urethra. The bladder is enclosed in a thin investing fascial sheath.

Investing fascia

The investing fascia reflects on to the lower ends of the ureters, combining with reflected bundles of detrusor, as Waldeyer's "ureterscheide" or sheath

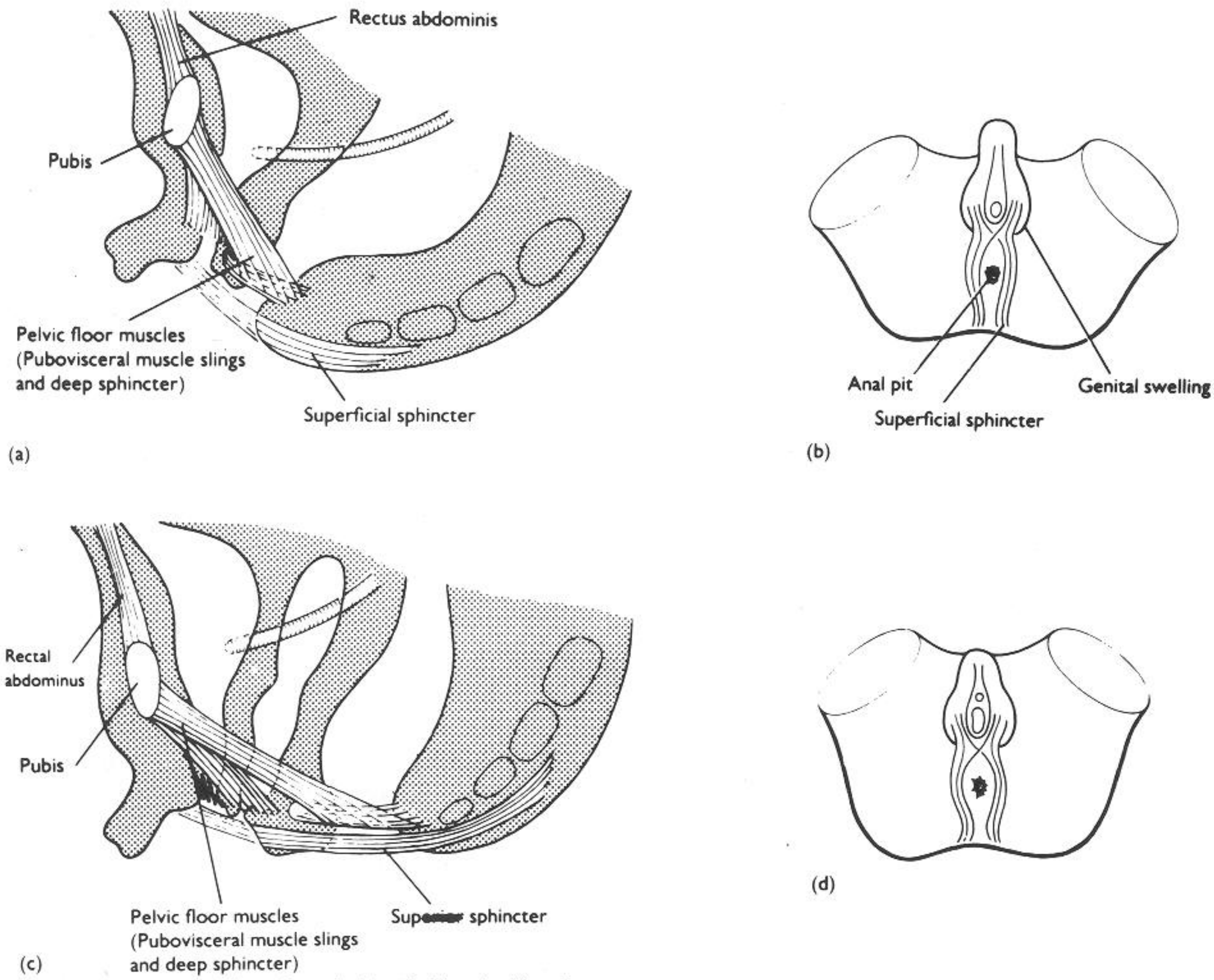


Figure 5. 8 weeks old embryo (8 mm), (a) and (b) male, (c) and (d) female. Diagrams (a) and (c) show the developing pelvic floor muscles and sphincters in sagittal section. Diagrams (b) and (c) show the developing voluntary sphincter fibres in relation to the anus, vagina and urethra (In: Surgery of Anus, Rectum and Colon. Keighley and Williams. London, Saunders) (46).

(60,64,69). It surrounds but is separate from the lower ureter until it blends with it 2-3 cm proximal to it's entry into the bladder.

The muscle layers of the body of the bladder

Though the presence of three smooth muscle coats is disputed (22,27) they are certainly present in our sections, a finding that agrees with most accounts. McCrea (1926) (53) describes three muscle coats (Fig. 6) over "the body of the bladder"; an outer incomplete longitudinal, a middle complete circular and a sparse inner longitudinal, sub mucosal, layer. He notes that the circular coat has a number of layers and that muscle bundles pass between the layers.

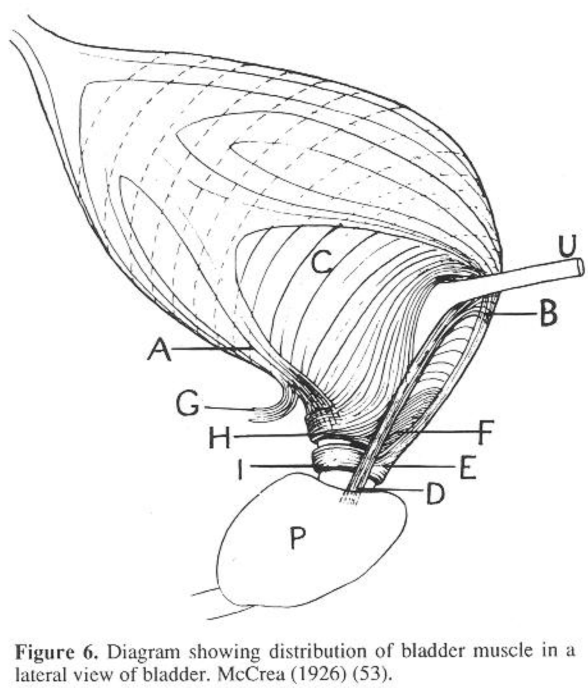


Figure 6. Diagram showing distribution of bladder muscle in a lateral view of bladder. McCrea (1926) (53).

The outer longitudinal muscle

At the apex of the bladder the outer longitudinal muscle is arranged in whorls, as it becomes continuous with the circular layer at the apex of the bladder [53]. Some fibres loop round the urachus [35]. The layer is most prominent anteriorly and posteriorly. The anterior and lateral fibres insert round the circumference of the bladder neck. A "transverse precervical arc", into which this layer is inserted, is described [21,35]. In our neonatal sections the muscle splits into a deep and superficial layer, at the level of the bladder neck. The superficial blends with the pubourethralis, as it approaches its insertion into the lower urethra. The deep inserts into the bladder neck, its fibers can be seen passing between the circular smooth muscle bundles (Fig. 7,9). Posteriorly the longitudinal muscle passes between the points of entry of the ureters. As it passes onto the back of the trigonal plate, it divides into two medial and two lateral bundles (Fig. 7).

The medial pass downwards and forward to insert into the apex of the dorsum of the trigonal plate [31,61] (Fig. 7). The lateral pass forward round opposite sides of the upper urethra, as the upper internal sphincter ("Bundle of Heiss" or "Sphincter Vesicae of Henle") (Fig. 7,8,9).

The "circular" muscle layers

The middle "circular" layer is formed by the interlacing smooth muscle bundles of the detrusor, where the multi-layer muscle bundles vary in direction and depth [21,27,53].

Inner longitudinal muscle layer

The inner longitudinal muscle layer of the body of the bladder continues down, as muscular slips, into the urethra [12,23,31,40,53]. These pass through the prostatic urethra into the membranous urethra, in the male, and to just above the external urinary meatus, in the female (Fig. 7,8,9).

The base of the bladder and upper internal urinary sphincter

The structure of the bladder base and upper urethra, and the arrangement of the circular smooth muscle bundles in this region, was accurately described in the last century [25]. Various names have been applied to the basal smooth muscle loops, such as "Fundus ring" [61], "Base plate" [29] or "Y-shaped bundle" [53].

The following structures can be identified:

i) Deep to the mucosal trigone, the trigonal muscle [4,5].

ii) The underlying fibro-muscular trigonal plate.

iii) A series of thick smooth muscle loops. These loops are continuous posteriorly with the trigonal plate, which completes the basal annulus and Hutch's "Base plate".

iii) The upper internal urinary sphincter ("Sphincter Vesicae" [25], "the Bundle of Heiss" [24]), is made up of smooth muscle loops which surround three sides of the upper urethra.

The mucosal trigone

Stratified cuboidal mucosa, rich in mucus glands, forms a smooth ▼ over the trigone. Its apex lies at the internal urinary meatus and proximal angles correspond with the ureteric orifices.

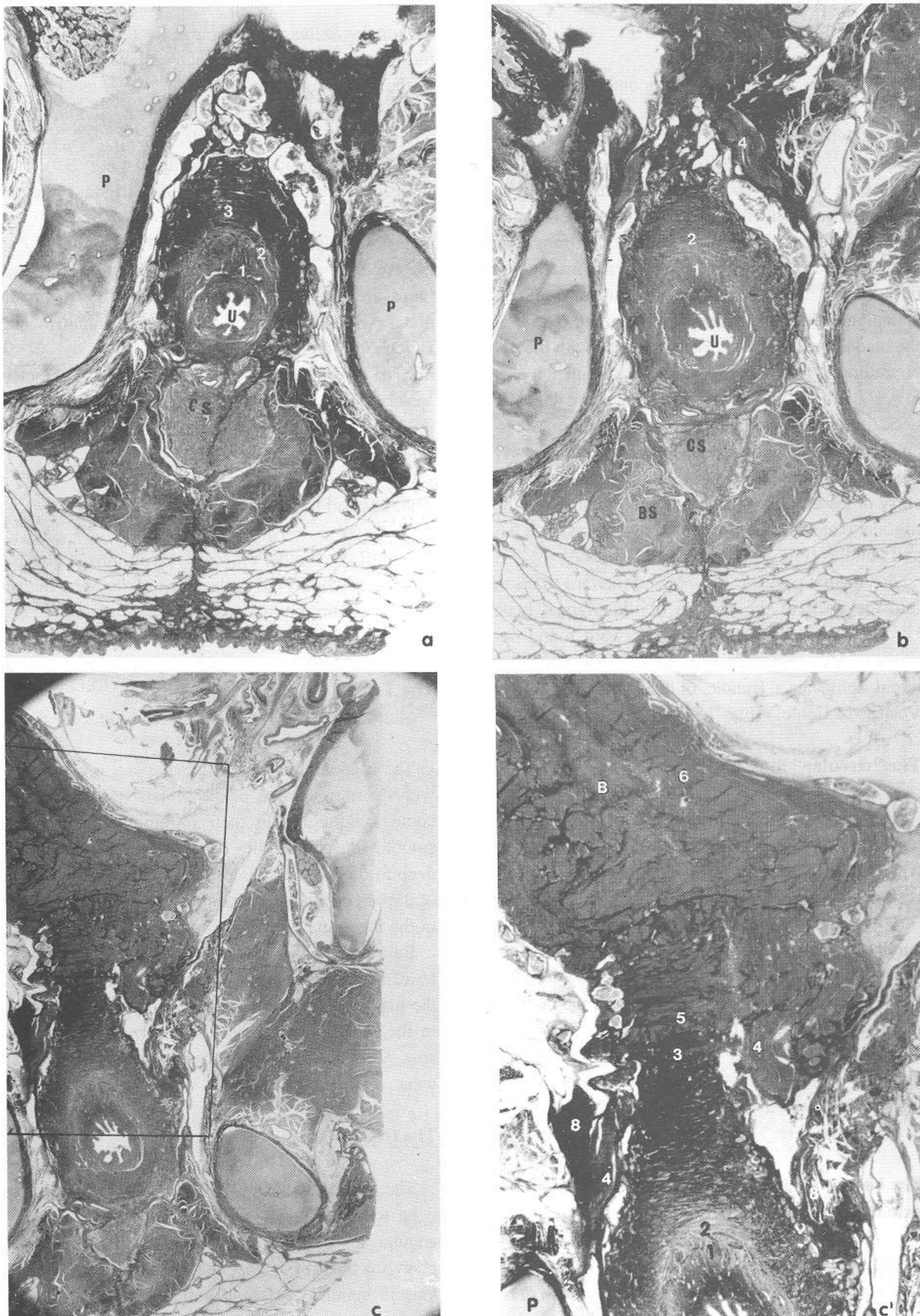
The Trigonal muscle (Bell's muscle) [4,5,13,16,17,18,19,21,38,45,50,51,53,62,63,64,70].

The trigonal muscle (Fig. 7,9) arises in continuity with the muscle coats of the ureters where they become longitudinal in their intramural portion. Its smooth muscle bundles fan out and course down deep to the trigonal mucosa. Above, the upper edge of the converging fibres contributes to the shallow V of the interureteric bar.

Below, the fibres converge and pass over the posterior lip of the internal urinary meatus to insert, in the male, into the region of the verumontanum and, in the female, just above the external urinary meatus. Medially the bundles contribute to the urethral crest.

The trigonal plate

The fibromuscular trigonal plate (Fig. 7,9), lying deep to the trigonal mucosa, conforms to its triangular shape, it's content of elastic tissue said to give it a yellowish appearance [7,56]. The smooth muscle bundles are small and lie transversely. On



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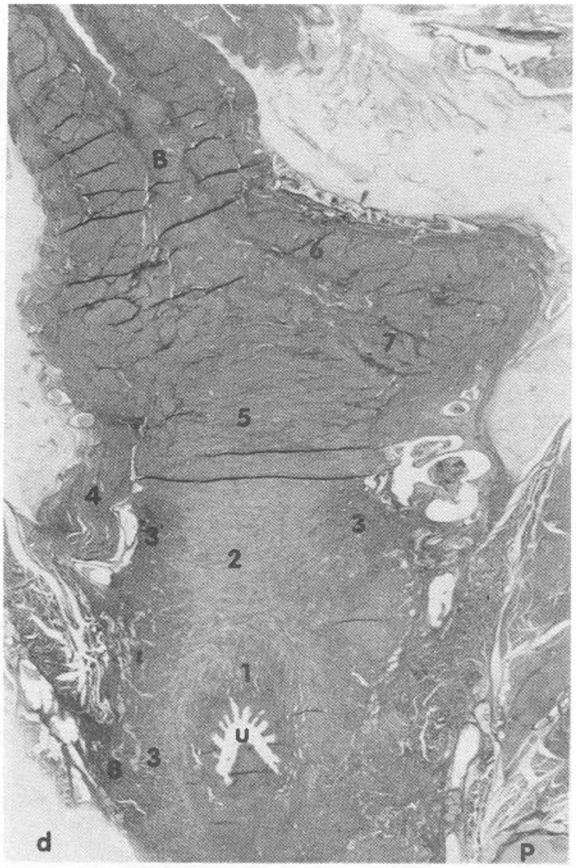
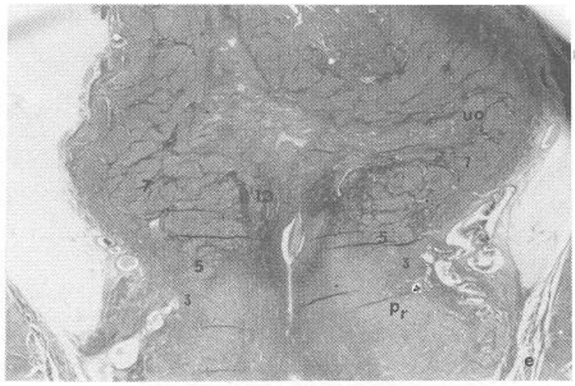




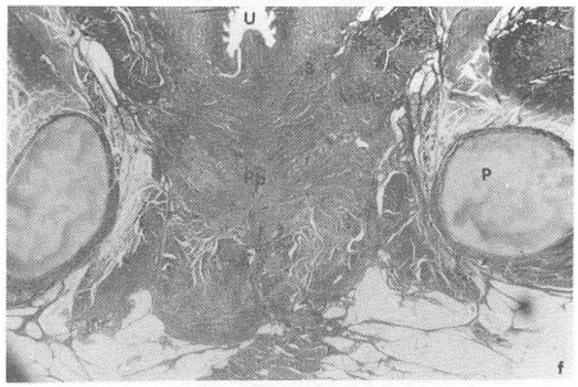


Figure 7. (a)-(h) Representative serial coronal sections from male neonatal pelvis (c': detail of c). Sections cut 7µ thick and stained P.T.A.H. and H.&E. *P: pubis, R: rectum, U: urethra, CS: corpora spongiosa, BS: bulbospongiosus, Pb:perineal body, Tr: trigonal plate, UO: ureteric orifice, A: anus, Pr: prostate, B: bladder, 1 inner longitudinal smooth muscle, 2 circular smooth muscle, 3 external urinary sphincter, 4 external longitudinal bladder smooth muscle and extensions, 5 upper internal urinary sphincter, 6 detrusor muscle, body of bladder, 7 basal smooth muscle loops, 8 and 9 pubourethralis, 10 trigonal muscle, 11 ureter, 12 insertion of puboanalis.*

three of its sides it is in continuity with the circular fibres of the basal loops, lying in the same plane. At its apex it receives the insertion of the upper fibres of the striated muscle sphincter, the compressor urethrogenitalis of Elliot-Smith [18,19]. Posteriorly the medial bundles of the posterior longitudinal bladder muscle inserts into its apex (Fig. 9). The tri-

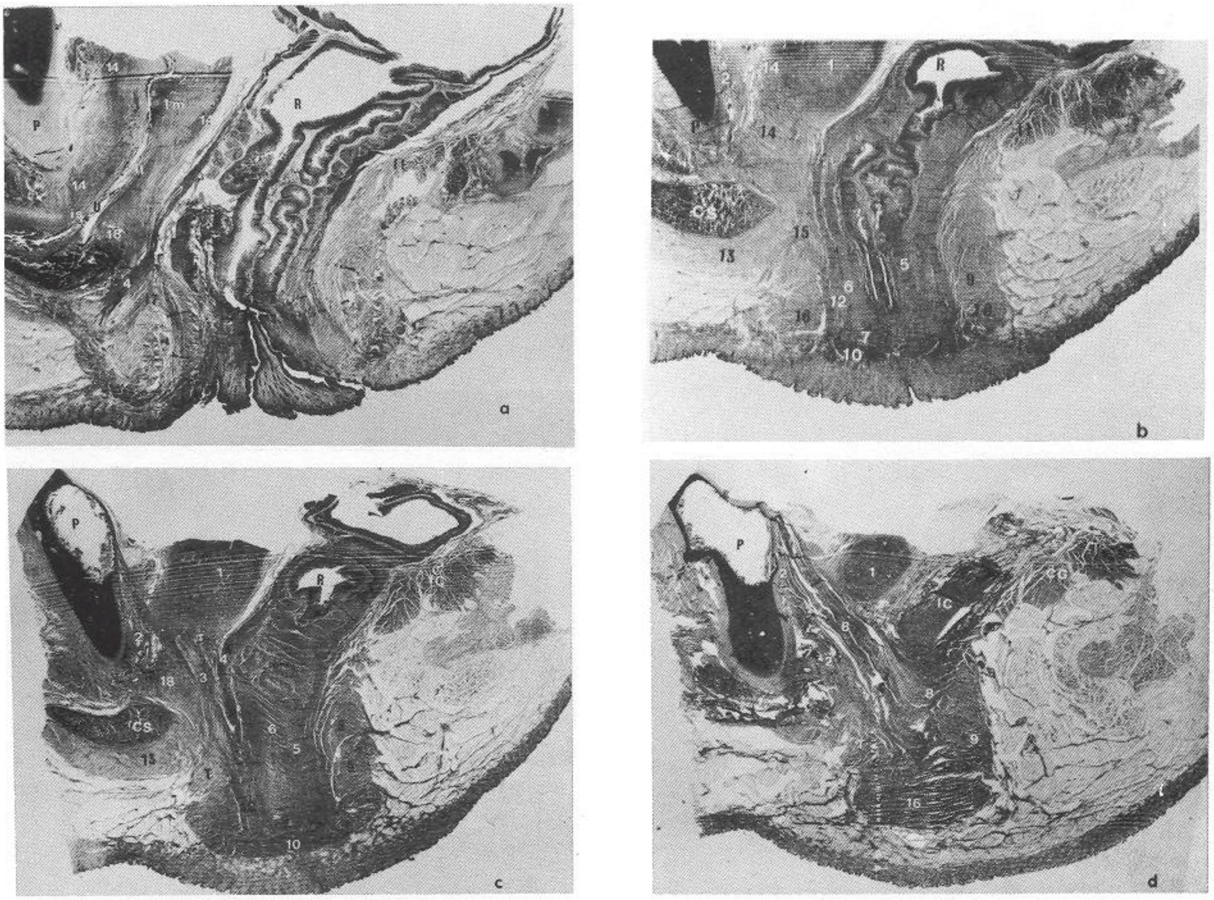


Figure 8. Representative serial sagittal (a) and parasagittal (b-d) sections of a neonatal male pelvis. Sections cut 7μ thick and stained P.T.A.H. and H.&E. *P: pubis, R:rectum, A:anus; U:urethra; is internal sphincter urinae, il inner longitudinal smooth muscle; I C ileo coccygeus, C G coccygeus, CS corpora spongiosa. 1 prostate, lateral lobes, 1 m median lobe, 2 pubourethralis (prostaticus), 3 puboperineus, 4 rectoperineus (urethralis) superiores, 5 longitudinal anal smooth muscle, internal anal sphincter, 6 superior and 7 inferior, 8 puboanalis and sling "semi tubular portion" of puborectalis (61), 9 pubosphincteric sling "cylindrical portion" of puborectalis (61) and deep anal sphincter, 10 superficial anal sphincter, 11 sacrococcygeal ligament, 12 conjoined longitudinal muscle, 13 bulbospongiosus, 14 external urinary sphincter, upper and lower parts, 15 perineal body, 16 deep anal sphincter, 17 inferior rectourethral muscle (58), 18 para urethral gland and its compressor (3).*

gonal muscle angles over its apex to continue down into the posterior wall of the urethra and urethral crest (Fig. 7).

Proximally, passing obliquely downwards and medially over its lateral angles, the ureters enter the bladder. To enter the bladder the ureters pass between "crura" of longitudinally oriented detrusor muscle at their attachment to the lateral angles of the trigonal plate [70]. The ureters are anchored by the reflection of the insertion investing vesical fascia and detrusor outside the bladder wall and inside by the attachment of the trigonal muscle and its extension down the urethra [45].

The upper internal urinary sphincter ("Sphincter Vesicae" [25], "Bundle of Heiss" [24])

The upper internal urinary sphincter is formed from the two lateral posterior longitudinal bundles of smooth muscle. These, having passed down onto the posterior surface of the base plate, course distally and forward below its apex. They pass round opposing sides of the proximal urethra to decussate with each other anteriorly, just below the rounded edge of the detrusor. In our neonatal sections the muscle fibres, after decussating, appear to fan out in the upper circular smooth muscle layer of the urethra, to insert into the perineal or urethral body.

The urethra

Considered here is the posterior and membranous urethra in the male and the whole urethra in the female.

Structures supporting the urethra (Fig. 11)

The muscles making up the levator ani can be divided anatomically into two groups, an anterior "pubovisceral" and a posterior "diaphragmatic" [44]. An anterior group arises from the back of the pubic bone and insert into pelvic viscera and the perineal body. They also provide muscular slings to the pelvic viscera, directly or indirectly. The division between the two groups, in the fresh dissections, lies between those muscles that arise directly from the pubis and those arising from the obturator membrane and ischium. There is no part which could be described as pubococcygeus. The posterior, diaphragmatic group, consist of two parts. More anteriorly an ileo-ischio-coccygeus, a thinner sheet of muscle, has a continuous origin along a line across the arcus of the obturator fascia and the ischium, as far as the ischial spine. More posteriorly the second part, the coccygeus, arises from the ischial spine [44,62]. The fibres of the former pass medially and back to insert into the ano-coccygeal raphe, the more anterior fibres turning under the more posterior to form an arch with the contralateral muscle. Coccygeus inserts into the anterior surface of the sacrum lateral to the sacral foramina [2,44,62]. The pubovisceral muscles support the pelvic viscera, the urethra and vagina and anorectum, in a quadrilateral space anteriorly. This space is bordered by the pubes and the anterior margins of the ileo-ischio-coccygei [2,44,62].

In the male two strap muscles, the pubourethralis ("puboprostaticus") arise from the back of the body of the pubis, pass downwards, medial and back to insert into the ipsilateral aspect of the urethra (Fig. 6,7,8,9). They insert between the two parts of the urethral striated muscle sphincter, the sphincter urogenitalis and the compressor of the membranous urethra [18,19]. Some of these fibres may contribute to the lower sphincter by passing across the urethra anteriorly to insert into the contralateral aspect of the perineal or urethral body [3,72]. The puboperinei also supports the urethra in the male. These strap like muscles, arising from the backs of the bodies of the pubes, pass back and down to insert into the apex of the perineal body (Fig. 8). Contraction of this muscle draws the urethra upwards and forward. Acting as a sling to the urethra, it compresses it, as an aid to voluntary control.

Though similar suspensory muscles are present in the female their distribution is modified by the descent of the sinovaginal bulb (Fig. 9,10,11). The pubourethralis and vaginalis appear as a continuous sheet, inserting anteriorly into the urethra as in the male, between the two parts of the voluntary sphincter, and posteriorly into the lower vaginal wall. Puboperineus is inserted into the perineal body, which is situated behind the vagina.

The muscles of the urethra

The inner longitudinal muscle

Anteriorly and laterally the inner longitudinal muscle coat of the bladder continues down into the urethra. These muscular and tendinous slips extend down to the external meatus in the female and the membranous urethra in the male [12,22,23,40,71]. Posteriorly the longitudinal fibres are in continuity with the trigonal muscle [4,5,13,17,18,18,19,38,51,53,62, 63,64]. The muscle extends down the back of the urethra as far as the external meatus in the female, but inserts at the verumontanum in the male. Fibres of the trigonal muscle contribute to the urethral crest.

Smooth muscle sphincters of the urethra

Below the upper internal sphincter the urethra has a continuous circular smooth muscle coat throughout its length in both sexes. This coat is said to be more prominent in the upper half of the urethra and made up of decussating spirals of fibres [31]. In our neonatal sections the layer is more uniform above and more prominent at the lower end. Hutch [31] believes that these fibres arise in the outer longitudinal coat of the bladder. In our sections the medial fibres at the bladder neck appear to contribute to the circular muscle bundles or pass between them into the inner longitudinal layer. In the male Hutch [34] notes that the "intra urethral lobes" of the prostate, the anterior, right and left lateral, develop and therefore enlarge within the circular muscle layer.

Although the urethra has a continuous circular smooth muscle layer there are two levels where the circular layer is prominent enough to form the upper and lower internal urinary sphincters.

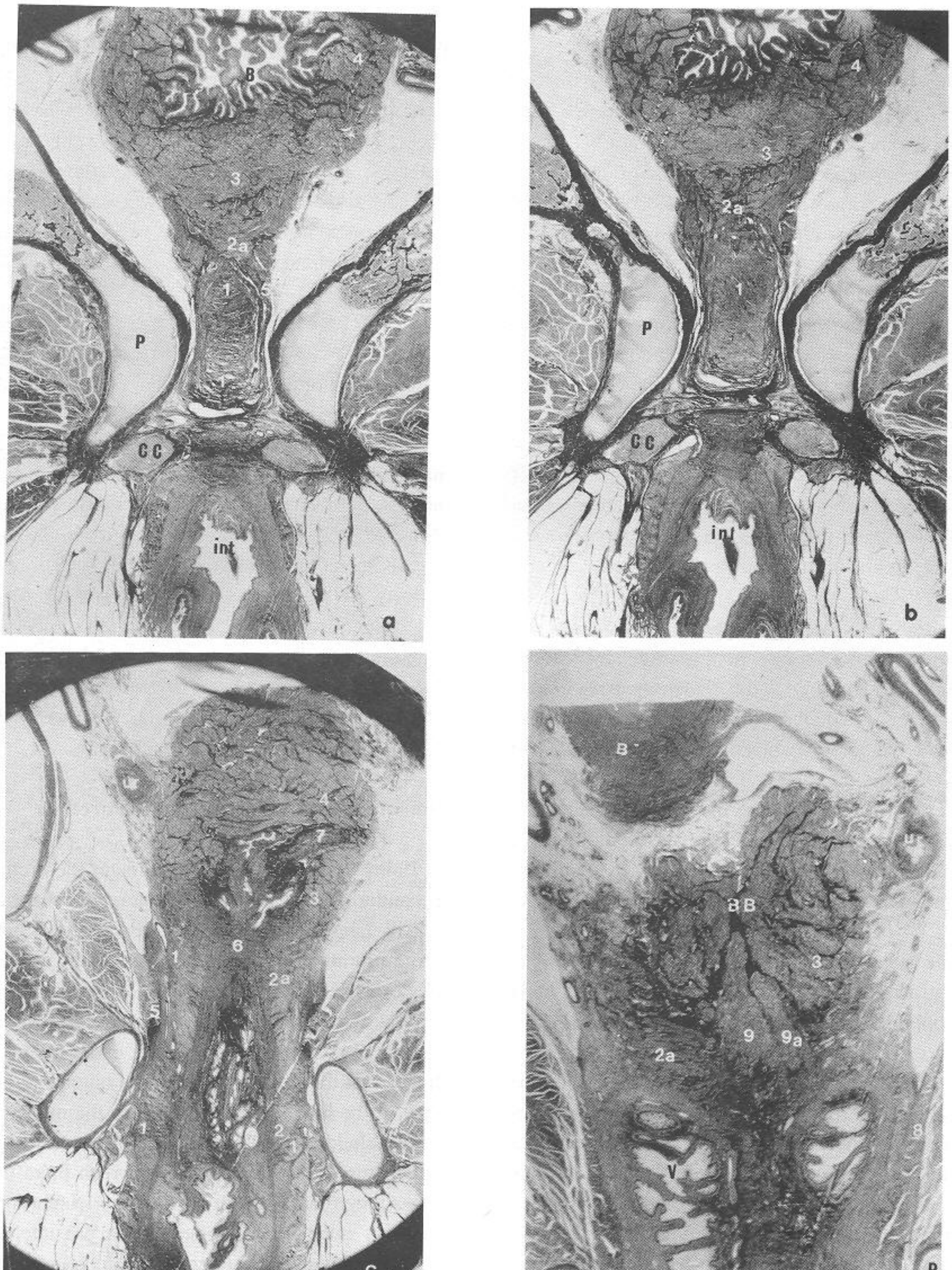
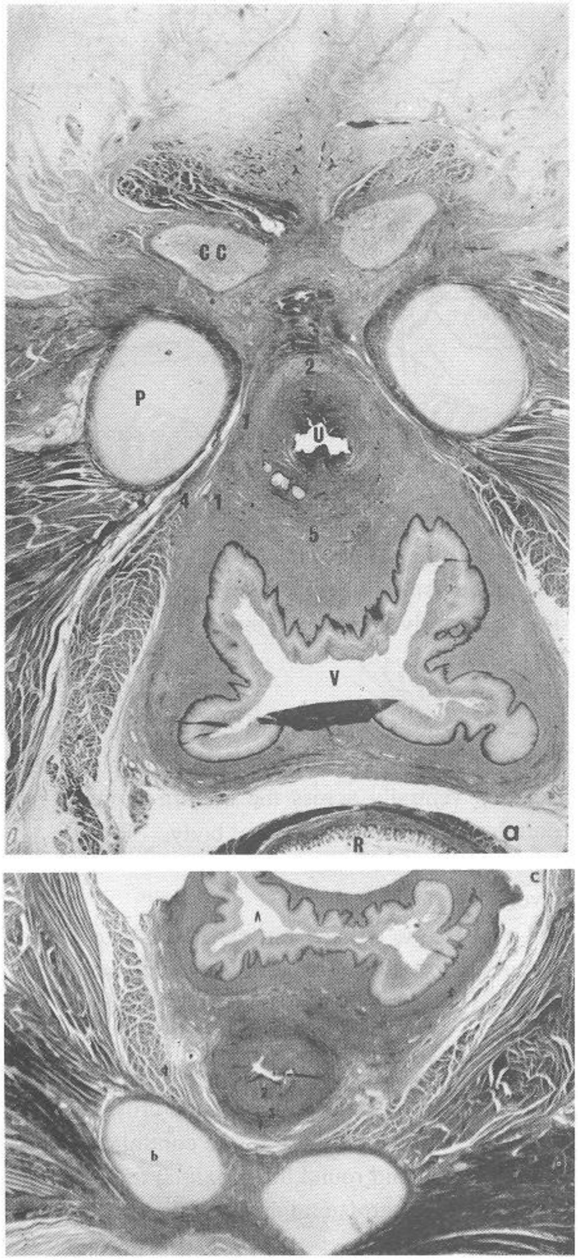


Figure 9. Representative serial coronal sections from a female neonatal pelvis sections cut 7μ thick and stained. P.T.A.H. and H.&E. (a-d). P:pubis, CC: corpora cavernosus, V:vagina, BB:bladder base, B: bladder, int:introitus, ur:ureter, 1 external sphincter, 2 internal sphincter, 2a upper internal sphincter, 3 basal rings, 4 detrusor muscle, body of bladder, 5 external longitudinal muscle and common insertion with pubourethralis, 6 trigonal plate, 7 ureteric orifice and trigonal muscle, 8 pubovaginalis, 9 medial and 9a lateral vesical posterior longitudinal bundles. **a)** This section, taken just behind pubic symphysis, shows the anterior wall of the urethra, the extent of the voluntary sphincter and the extension of the outer longitudinal bladder muscle lateral to the urethra. **b)** A more posterior section showing decussating upper fibres of the voluntary sphincter. Above this the smooth muscle bundles of the upper internal urinary sphincter. **c)** This section passes through the trigonal plate at the level of the bladder neck. Above the left ureteric orifice and the trigonal muscle arising from it is shown. Below the arrangement of the circular smooth muscle of the urethra is very similar to that of the internal anal sphincter. **d)** The section through the back of the bladder shows the medial and left lateral bundles of the posterior longitudinal bladder muscle.



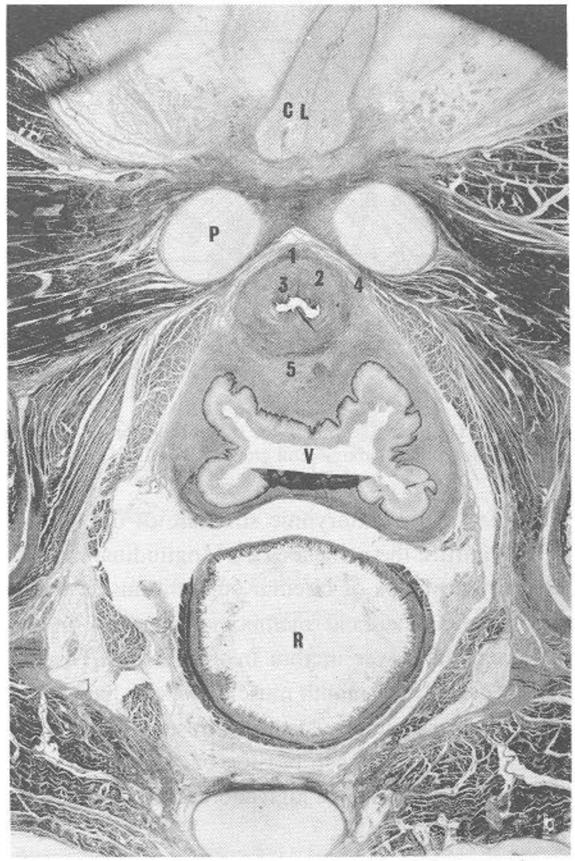


Figure 10. Representative serial transverse sections female neonatal pelvis. Sections cut 7μ thick and stained H.&E. or P.T.A.H. P: pubis, U: urethra, R:rectum, CL: clitoris, CC corpora cavernosus, V: vagina, 1 external urinary sphincter, 2 circular smooth muscle coat, 4 pubourethralis/vaginalis, 5 urethral body. **a)** Lower external urinary sphincter fibres passing back into vaginal wall and inserting into urethral body. The circular smooth muscle is prominent (lower internal urinary sphincter). The pubourethralis is seen at its insertion into urethra and vagina. **b)** At a higher level the fibres of the external sphincter no longer pass back into the vaginal wall. The urethral body is much narrower the circular smooth muscle layer is much less prominent. **c)** At a higher level there is a definite groove on either side between vagina and urethra. The urethral body is now very narrow. Though the inner longitudinal layer of smooth muscle is prominent the circular layer is not.

Lower internal urinary sphincter [14,16,17,38,55]

The smooth muscle fibres of the lower internal sphincter lie more transversely and in the same plane as the circular muscle above, but are distinct from them. In the male the muscle arises on either side from the perineal body, looping round the membranous urethra within the annulus of the striated membranous urethral sphincter. In the female the sphincter arises from the urethral body (urethro-vaginal septum) and loops round the urethra just inside the external urinary meatus. In the male the annulus is completed posteriorly by the perineal body and in the female by the urethral body. The fibres of the lower internal sphincter, in the female, can be followed back through the urethral body into the lower vaginal wall. In the male they can be traced back through the perineal body, as the inferior rectourethral muscle or Roux's muscle [59], into the lower internal sphincter ani [43] (Fig. 8). This suggests a common origin from a primitive cloacal sphincter.

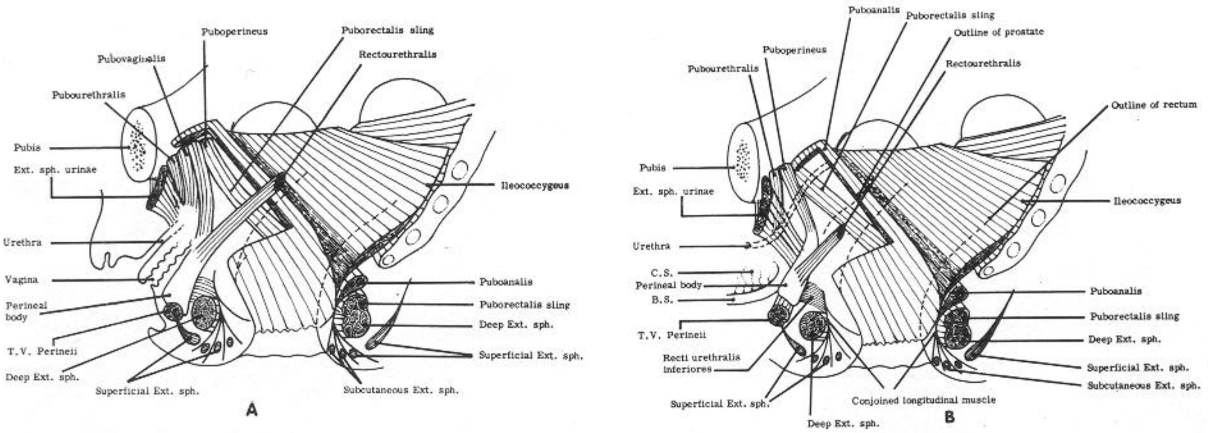


Figure 11. Diagrams illustrating the subdivisions of the levator ani in the male and female. The puboanalis is cut away to demonstrate the other muscles of the "pubovisceral group " (Lawson, 1974) (44).

Studies of the embryonic structure of the urethra (11,15) confirm the presence of a longitudinal muscular coat and loops of circular smooth muscle round the inframontanal and membranous urethra in the male and the lower urethra in the female. The authors regard these smooth muscle loops as having developed as a separate system. Corresponding smooth muscle bundles are seen passing back round the rectourethral fistula in male high anorectal agenesis.

Voluntary (striated muscle) sphincters
(Fig. 7,8,9,10)

In both male and female the urethra has a striated muscle coat throughout its length but in neither is there a complete striated muscle annulus. It has long been recognised that the voluntary sphincter muscle, the "urogenital sphincter" (62), consists of two parts. These comprise a lower sphincter, the "compressor of the membranous urethra" and an upper, the "urethrogenital sphincter" (18,19,25,53).

Barkin (3), while recognising the two main divisions, divided the urethral striated sphincters into four levels, for descriptive purposes (3) (Fig. 12). He subdivides the fibromuscular perineal body into a urethral body anteriorly and a perineal body posteriorly. The bodies are fused in the male but separated by the vagina in the female (Fig. 13).

Divisons of the external urinary sphincter

	MALE	FEMALE
I	Membranous	Distal
II	Supramembraneous	Upper middle
III	Prostatic	Lower middle
IV	Bladder neck	Bladder neck

Level II.
At Level II the striated muscle completely encircles the urethra ventrally and laterally inserting on either side, posteriorly, into the urethral body.

Level I.
At Level I similar loops occur but some of the muscle bundles arise from the sides of the pubic arch and loop ventrally across the urethra to insert into contralateral side of the urethral body.

Level III.
At Level III the striated muscle fibres take a more oblique course so that ventrally their arches almost reach the bladder neck.

Level IV.
At Level IV the fibres from one side cross the midline, decussating with those of the contralateral side, to continue up and round the proximal urethra to insert into the posterolateral angle of the bladder neck (trigonal plate).

In the female, where anteriorly and laterally the urethra has a continuous striated muscle coat, the annulus of the sphincter is completed posteriorly by the urethral body, below, and the base plate above. The fibres of the lower sphincter loop round the urethra from one side of the urethral body to the other. Above the insertion of the pubourethralis the muscle loops pass with increasing obliquity up the front of the urethra. The upper bundles, now decussating with those of the contralateral side, continue to spiral up round the urethra to insert into the opposite sides of the apex of the base plate.

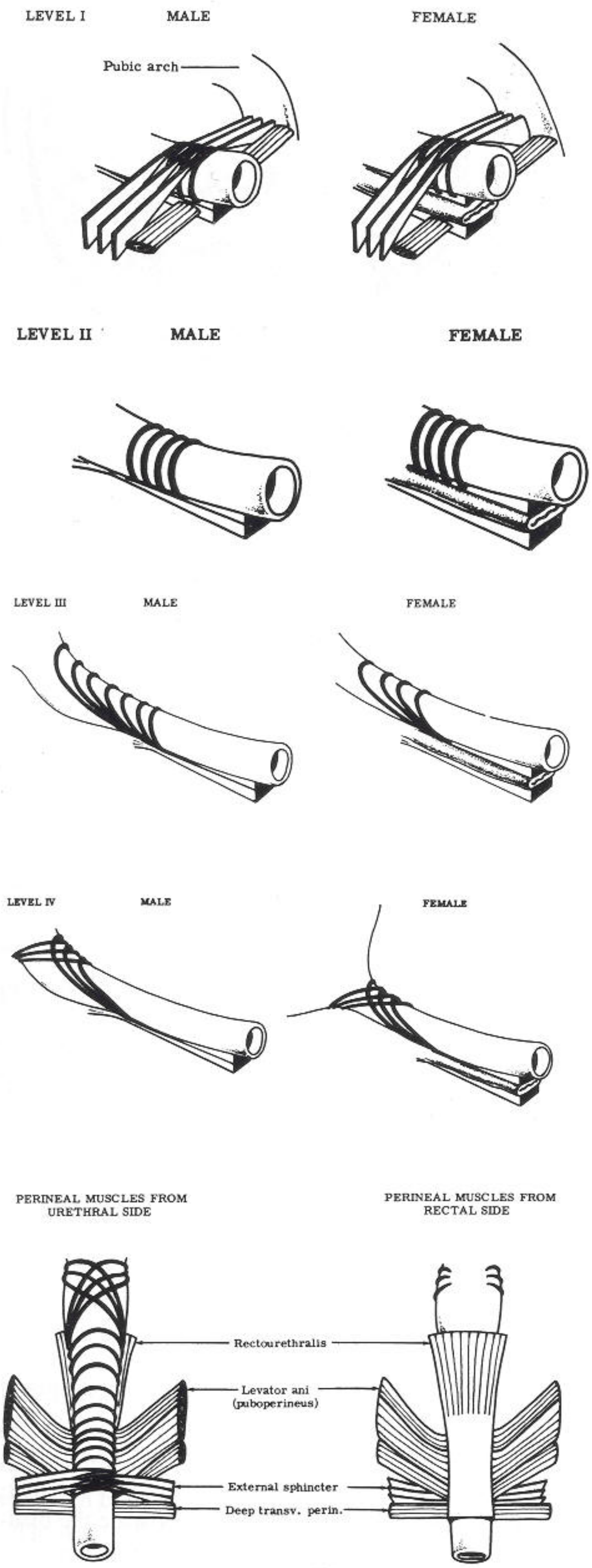


Figure 12. Diagrams illustrating the arrangement of the striated muscle of the voluntary urethral sphincter at the levels described (3).

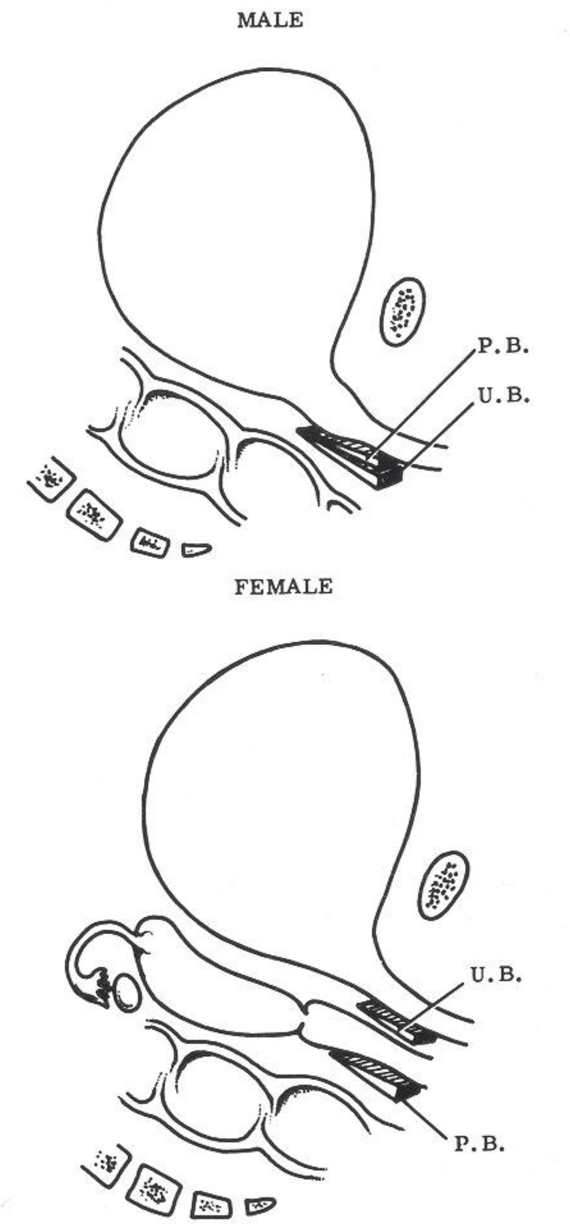


Figure 13. Diagrams illustrating the concept of a urethral (U.B.) and perineal body (P.B.), fused in the male (3).

Posteriorly between the urethral body and the base plate there is an unsupported segment of urethra, an area of relative weakness seen bulging on micturating cystography. Posteriorly striated muscle bundles of the lower external sphincter are seen to extend, through the urethral body on either side into the wall of the vagina [38,50] and in the fetus surrounding both vagina and urethra [14].

In the male the distribution the striated muscle at Level III and IV is modified by the development of the prostate. In the fetus [14] and neonate the prostate lies, predominantly, posterior to the coronal axis of the urethra. The enlarging lateral lobes displace the voluntary sphincter fibres forward and up. It is likely that the fibres of Levels III and IV are the "vertical" fibres noted, anteriorly, in some studies [52,63,71] and those of Level IV the more transverse fibres described by Henle as the "sphincter vesicae externus" (external vesical sphincter). These fibres are seen round the upper urethra between the bladder neck and the prostate [25] (Fig. 7).

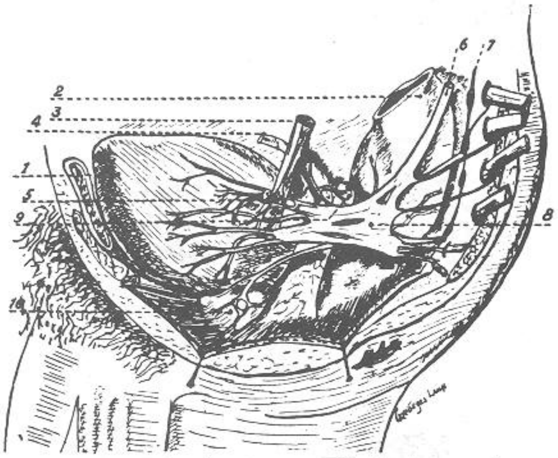
The fibres at Level IV insert, laterally, into the apex of the trigonal plate. This allows the medial posterior longitudinal bundles of smooth muscle to pass downwards and forward between them, to become the upper internal sphincter.

Below the trigonal plate, between the lateral lobes of the prostate, the verumontanum and the entry of the ejaculatory ducts, there is an area unsupported by voluntary muscle and poorly supported by the developing and extra-urethral medial lobe. It is here that the urethra dilates back below the fibromuscular trigonal plate to give the prominent "posterior shelf" seen in posterior urethral valve obstruction.

The loops of the voluntary sphincter complex increase in length and obliquity as they are followed upwards. This could explain why the urine, contained in the urethra at the end of micturition, is returned to the bladder [8,39]. In distal urethral obstruction, as in spinning top urethra in the female, this residue may amount to a significant volume. Fibres of the voluntary sphincter also compress the paraurethral glands [3], providing a potential inoculum of bacteria into the urine returned to the bladder.

Nerve supply

The autonomic nerve supply of the lower urinary tract reaches it by two routes. The main supply reaches it from the lumbosacral outflow, via the hypogastric and pelvic plexuses [47] (Fig. 14). Preganglionic fibres in these plexuses reach a large collection of ganglion cells behind the base of the bladder. Further autonomic nerve fibres, from the lumbar ganglia, reach the bladder along the ureters. The urethra has also a dual somatic nerve supply. The urethra, below the insertion of the pubourethralis (puboprostaticus), is supplied by branches of the pudendal and perineal nerves. These nerves derive from the anterior primary rami of the second, third and fourth sacral segments.



Left hypogastric ganglion, lateral aspect: 1: bladder, 2: rectum, 3: ureter, 4: vas deferens, 5: vesical nerves, 6: left hypogastric nerve, 7: sacral sympathetic chain, 8: hypogastric ganglion, 9: seminal vesicle, 10: prostate gland. The parasympathetic nerves from the second and third sacral nerves to the hypogastric ganglion are also shown (After Laux).

Figure 14. The autonomic nerve supply to the bladder and upper urethra. Note that the "hypogastric plexuses" are now usually called the pelvic plexuses (Learmonth 1931) (47).

The pelvic floor nerves (Fig. 15) supply the urethra above the pelvic floor [37,44,61,68]. These somatic nerves have a lower root value than the pudendal nerves, arising from the anterior primary rami of the third, fourth and fifth sacral segments. The pelvic floor nerves pass forward over the levator ani, either as separate nerves or single trunks. As they cross over the upper surface of the levator ani they lie between the muscle and the investing layer of pelvic fascia, separated from the pelvic plexuses. These nerves supply lateral branches to the levator ani and four haemorrhoidal nerves that enter the anal canal above the insertion of the puboanalis. They complete their course by entering the urethra above the insertion of pubourethralis.

ANATOMY, AS APPLIED TO FUNCTION

Bladder filling and emptying

The well-developed multilayer interlacing muscle bundles of the circular layer of the body of the bladder are ideally suited for its function of filling, storage and expulsion of urine. The relatively poorly developed longitudinal muscle layers provide the bladder with an adequate anchor during contraction.

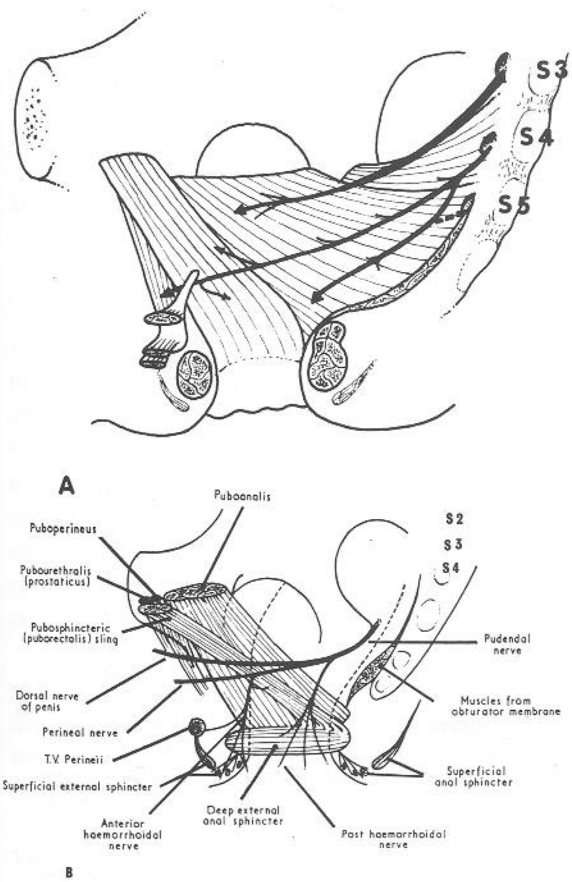


Figure 15. Diagrams showing the course to the lower urinary tract and root value: a) of the pelvic floor nerves on the upper surface of the levator ani, b) of the pudendal nerve below the pelvic floor.

The base of the bladder

The role of the bladder base is much more complex. Taken as a whole the trigonal plate and the series of prominent loops of smooth muscle that encircle the internal urinary meatus appear to play a part in both bladder filling and emptying. Flattening of the bladder base occurs during filling but during micturition it assumes a conical configuration [28-35]. This may result from the relaxation of these loops, or from an active contraction of the loops wide of the internal meatus. The former would suggest a similarity in function to that of the upper part of the internal anal sphincter, where a similar relaxation occurs with the onset of a rectal contraction, prior to relaxation of the lower internal sphincter [41].

The trigonal muscle angles over the apex of the trigonal plate. Contracting during micturition, it will not only depress the apex of the trigonal plate but render the insertion of the ureters more oblique by drawing the intramural ureter into the bladder. This may account for the relationship between vesico-ureteric reflux and wetting due to bladder instability [45].

How does the urethra close?

The normal urethra and its sphincter mechanism provide a water-tight closure, both at rest and with activity. When required it can open rapidly to give a good stream of urine. Similarly at the end micturition rapid closure allows an immediate end to micturition.

Closure must be maintained for long periods with the minimum expenditure of energy. Three mechanisms are involved, a mucosal choke, the smooth muscle sphincters and the striated muscle sphincters and slings.

A major factor influencing the rate of flow of a fluid through a tube will be its cross sectional area. The maximum variation in the cross sectional area of the lumen in a sphincter zone, during opening and closure, is obtained by a choke mechanism [10]. A mucosal choke is seen in the mucosal lining of three sphincters, those at the lower end of the oesophagus, the anus and the urethra. The folds in the anus [43,44] and the urethra [31] are rendered more prominent by the inner longitudinal muscles and vascular connective tissue. Rapid closure is ensured by the striated sphincters and sustained closure by the smooth muscle sphincters.

The mucosal choke or throttle

When fully open the lumen the urethra is a smooth walled tube. Closed the wall is thrown into 6-8 folds, one of these provided by the urethral crest. The lumen appearing stellate on cross section (Fig. 6,9).

The hydrodynamics of the cardia has been elegantly shown by Chrispin AR, Friedland GW, Wright DE (1967) [10]. Though their account refers to the flow of liquids through the oesophageal cardia the same principles can be applied to the flow of urine through the urethra. These authors compare the flow through cylindrical and star shaped tubes. They state Poiseuille's equation (Fig. 16).

$$Q = \frac{\Delta p \, \pi r^4}{\Delta l \, 8\mu}$$

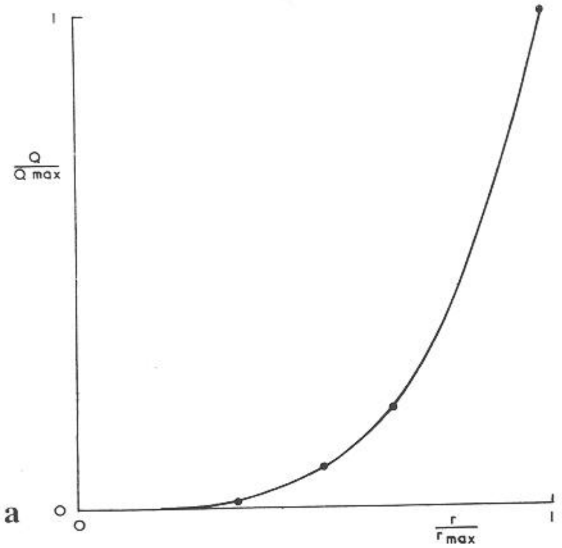


FIG. 1. *Poiseuille equation Q $\frac{\Delta p}{\Delta l}\frac{\pi r^4}{8\mu}$ Kr^4. Graph of $\frac{Q}{Q\ max} = \left(\frac{r}{r\ max}\right)^4$ against $\frac{r}{r\ max}$ where Q is flow at radius r and Q max is the maximum flow at maximum radius r max. This demonstrates the influence of change of radius on flow.*

Figure 16. a) and b) The choke effect of flow of liquid through a stellate tube. Poiseuille's Law (Chrispin, 1967) (10).

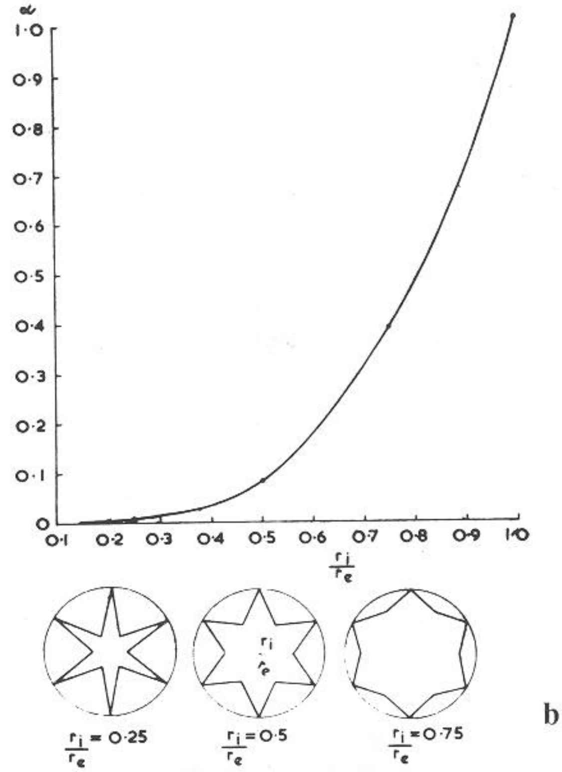


FIG. 2. *Hydraulic capacity of a star-shaped pipe Q αQp where Q is actual flow and Qp is given by $Qp = \frac{\Delta p}{\Delta l}\frac{\pi r_e^4}{8\mu}$ (Poiseuille flow for a circular pipe of radius r_e) and α is the coefficient for a star-shaped pipe. Graph of α against $\frac{r_i}{r_e}$ where r_i is the internal radius and r_e is the external radius. For example, when $\frac{r_i}{r_e}$ 0·25, α 0·006 and hence Q 0·006 Qp a reduction of flow to 0·6% and when $\frac{r_i}{r_e}$ 0·75, α 0·384 and hence Q 0·384 Qp –a reduction of flow to 38·4%.*

The more closely the star shape approximates to that of a cylinder the more nearly α 1. The deeper the indentations into the lumen the more closely does α approach 0. This illustrate the 'choke effect' of a star-shaped tube.

Where **Q** is the flow of a fluid of π viscosity through a cylindrical tube of radius **r** and length Δl where the difference in pressure along the tube is **Δp**. They note that the viscosity is constant and the pressure gradient and the length of the tube varies little from moment to moment, but the calibre changes considerably. In the Poiseuille equation the effect of changes in calibre is raised to the fourth power.

It is unlikely that the mucosal perimeter, determined by the mucosa, changes much during the contraction and relaxation of the muscle of the sphincter zones. During closure the mucosa is thrown into folds, giving a cross section of the lumen a stellate appearance, but on relaxation the folds become progressively less evident, until they disappear. The changes in the cross sectional characteristics of the lumen result in considerable changes in the hydraulic capacity of the urethra. A coefficient α is introduced so that q=αQp where

$$Qp = \frac{\Delta p\ \pi re^4}{\Delta l\ 8\mu}$$

Where Q represents the actual flow.

α is a dimensionless coefficient. This coefficient is dependant upon the ratio of the cross sectional area of the "lumen" to the perimeter of the "lumen". The lumen being the effective conduit for flow. It can be seen that the less the lumen is like a cylinder the less is its hydraulic capacity. This means that when the sphincter zone is incompletely open flow is very much less than it would be if one was considering a cylinder of circular cross section and radius re. Thus the sphincter zone, when it is incompletely open, has the characteristics of a highly efficient choke mechanism but when fully open the lumen permitting maximal flow. A mechanism that permits a rapid increase in flow when the sphincter relaxes and rapid reduction when it contracts.

In the anal canal and urethra the fold formation is enhanced by the submucosal longitudinal muscle bundles. The 6-7 folds seen in these sphincter zones are considered optimal for this choke effect [9].

What muscles maintain closure?

The voluntary sphincter muscles are small fibre [71], high energy rapid acting muscles, ill suited for sustained contraction. They are an unlikely cause of persistent outflow obstruction. The smooth muscle sphincters, on the other hand, are well suited to long term contraction. If comparable with the smooth muscle internal anal sphincter the internal urinary sphincter can sustain prolonged closure by rhythmical contractions. They resist penetration with an increase in tone, unless active relaxation (inhibition) takes place.

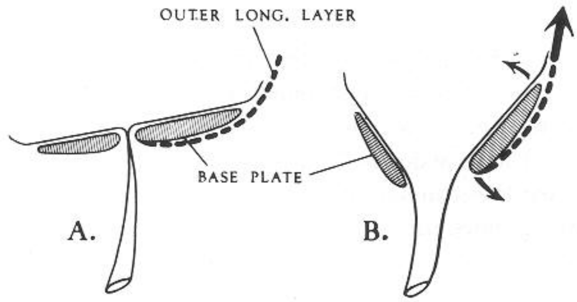
Contraction of the loops of the upper internal urinary sphincter (Bundle of Heiss), passing down behind the trigonal plate and round the upper urethra, both elevates the trigonal plate and draws it forward into the U-shaped lumen.

Voluntary closure

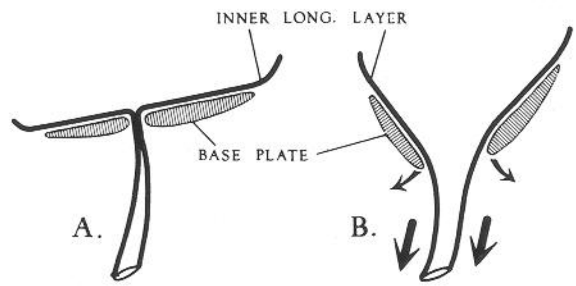
The striated sphincters and slings have two main roles. The first is to ensure rapid closure of the urethra at the end of micturition. The second is to augment urethral closure during periods of muscular activity resulting in raised intra-abdominal pressure. They also have a role in ejaculation and may through their insertion into the base plate assist the voluntary initiation of micturition. The voluntary sphincters in the female extend the length of the urethra but, by nature of their insertion, leave an area below the base plate relatively unsupported. It is this area that is seen bulging during micturating cystography.

What mechanisms aid opening of the urethra?

Contraction of the fundal detrusor and relaxation of the internal urinary sphincters occurs synergistically in the normal. At the onset of micturition the passive relaxation of the bladder base and upper urethra is aided by contraction of the inner longitudinal muscle of bladder and urethra and by the trigonal muscle (Fig. 17). These muscles pass at an



Schematic drawing demonstrating relationship between inner longitudinal muscle layer of bladder and base plate when base plate is flat A. Contraction of inner longitudinal muscle layer opens base plate in B. Contraction of superficial trigone opens base plate in exactly same way.



Schematic drawing demonstrating relationship between trigonal part of base plate and outer longitudinal muscle layer inserting into tip of trigone with base plate in flat position. A. Contraction of this part of outer longitudinal layer around full volume of urine pulls caudal end (tip) of trigone downward and outward and cranial edge upward and inward B.

Figure 17. Two diagrams illustrating Hutch's concept of the role of the Inner longitudinal smooth muscle layer and the median band of the posterior outer longitudinal and their relationship to the "base plate" (trigonal plate and basal muscular rings) (Hutch, 1966) (30).

angle over the closed bladder neck. The synergistic contraction of the trigonal muscle, and the medial bands of the posterior vesicle longitudinal muscle attached to it, depresses the apex of the trigonal plate (Fig. 17). Entry of urine into the urethra is followed by relaxation of the lower internal sphincter urinae. This is a response comparable with relaxation of the lower part of the internal sphincter ani that follows the entry of stool into the upper anal canal [41,43].

The role of the urethral sphincters with ejaculation

The anatomical arrangement allows the upper internal sphincter to remain closed and the lower to relax as semen enters the posterior urethra, preventing retrograde ejaculation. Contraction of the upper striated sphincter would assist expulsion, while relaxation of the inferior sphincter allows the progress of the semen into the urethral bulb.

The pubovisceral muscles, pubourethralis (prostaticus), vaginalis and puboperineus support the lower urinary tract during the downward pressure of raised intra abdominal pressure. By it's attachment to the lower urethra the pubourethralis, contracting during micturition, supports the urethra and will draw the lower urethra apart.

Summary

The mesh like structure of detrusor muscle of the body of the bladder is ideally suited to its role a a relaxing and contracting reservoir. It contracts against its anchors to the pelvic floor and urethra.

The concentric rings of smooth muscle, continuous with the fibro-muscular trigonal plate posteriorly, surround the internal urinary meatus to form an anatomical and physiological entity, the bladder base. The bladder base, which becomes flatter during filling assumes a conical shape during micturition.

Both the female urethra and the posterior urethra have continuous inner longitudinal and circular smooth coats. The circular smooth muscle coat is more prominent round the upper urethra, where it is formed from loops of posterior longitudinal bladder muscle, and inferiorly, where the loops arise from the urethral or perineal bodies.

The female urethra has a continuous striated muscle sphincter, prominent at the lower and upper ends. In the male the posterolateral enlargement of the prostate interrupts the continuity of voluntary sphincter in the prostatic urethra, displacing the loops forwards and upwards. The upper sphincter is therefore more prominent. The prominent membranous urethral sphincter lies below the enlarging prostate.

As superior internal urinary sphincter relaxes the mucosal folds flatten. The internal urinary meatus is actively opened by the combined action of the internal longitudinal muscle, the trigonal muscle, and the external longitudinal muscle. The contraction of the trigonal muscle draws down the intramural segments of the ureters.

Bladder neck and urethral closure are maintained, at rest, by a mucosal choke and a low energy smooth muscle sphincter. Closure of both upper and lower parts of the urethra is reinforced by an increase in the urethral smooth and striated muscle sphincters tone, with raised abdominal pressure. The pelvic floor insertions (pubovisceral muscles) provide support and slings to the urethra.

Micturition is both an active and passive function. It involves the contraction of the bladder detrusor and longitudinal coats and synergistic relaxation of the muscle loops of bladder base and the smooth muscle sphincters. The internal meatus is then actively opened by the inner and outer longitudinal muscle. The flattening of the vertical mucosal folds ensures a rapidly increasing urethral lumen. Micturition may be assisted by raised abdominal pressure.

Voluntary control can be exercised by the voluntary sphincters and the pelvic floor slings. In the female the urethra is enclosed in the voluntary sphincter. In the male the pubo-perineus, inserted on either side into the perineal body acts as a sling. In the female the insertion of the pubovaginalis into the urethro-vaginal septum may act in a similar manner. Contraction of voluntary sphincters, which are rapid and effective in response to stress, are not sustained.

Maintaining closure of the upper internal sphincter while relaxing the lower and contracting the voluntary sphincters ensures the forward progress of the semen into the anterior urethra.

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Jeremy O.N. Lawson, FRCS
Paediatric Surgeon and Urologist, Emeritus
St. Thomas and Westminster/Chelsea Hospitals
London