Medical Hypotheses 140 (2020) 109642

Contents lists available at ScienceDirect

Medical Hypotheses

journal homepage: www.elsevier.com/locate/mehy

"Fossa navicularis" and "septum glandis": A "flow-control chamber" for the male urethra?☆

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ABSTRACT

A clear understanding of the normal anatomy of the glanular urethra is essential for anatomical reconstruction of the male urethra. In hypospadias surgery, tubularization of the neourethra over a catheter or stent has been the standard method for decades. However, the male urethra is not a tubular structure with uniform configuration and diameter by forming a fossa (navicularis) in the glans penis. We recently investigated the structural anatomy of the glanular urethra using magnetic resonance imaging (MRI). We have shown that the male urethra does not have a uniform tubular structure and not covered by the corpus spongiosum to the end. The glanular urethra that forms the "fossa navicularis" has a wider caliber than the proximal urethra. Its vertical elliptical shape resembles a laterally compressed slit-like passage. The fossa navicularis is covered by a thin layer of fibrous tissue ("septum glandis") which is an extension of tunica albuginea of the corpus cavernosum and the corpus spongiosum. Our hypothesis is based on the results of MRI of the glanular urethra and the basic principles of fluid dynamics. We analyzed the flow dynamics of urine on this particular component of the urethra in terms of shape and structural properties. Because of its wider caliber than the proximal urethra, the glanular urethra (fossa navicularis) should cause an increase in pressure and a decrease in velocity of the urine flow. The navicular shape of the fossa and its elliptical external opening (the meatus) should allow urine to be expelled at higher flow rates and at opposite angles at the upper and lower corners which make the wave-like shape of the urine. It can be said that the changes in the volumetric form, pressure and velocity, as well as the wave-like shape of the urine flow are caused by the "fossa navicularis" covered by the "septum glandis". We propose that the "fossa navicularis" and "septum glandis" play a role as 'flow control chamber" in controlling the flow of the urine exiting the urethra, which must be taken into account for successful functional reconstruction of hypospadias.

Introduction

Almost all hypospadias repair techniques include urethral reconstruction over a catheter or stent, based on decades-old procedure [1]. However, the male urethra is not a tubular structure with uniform configuration and diameter by forming the "fossa navicularis" at its terminal portion. The "fossa navicularis" has distinct attachments in the glans penis, particularly with the "septum glandis", a fibrous tissue composed of collagen and elastic fibers that surrounds the fossa navicularis [2–6].

Urodynamic studies of the bladder and urethra are well known and there is an increasing interest in assessing urethral function after hypospadias repair [7–9]. The idealized model problems, which characterize the main features of the fluid flow in the body, are investigated (either experimentally or theoretically) in biological fluid dynamics. However, only several mathematical modellings of fluid flow were performed in the urinary tract [10–13]. In the present study, we investigated the anatomical features of the glanular urethra and its importance for urine flow dynamics and the results are discussed in relation to urethral tubularization in hypospadias surgery.

Hypothesis

We have previously demonstrated the detailed structural anatomy of the glans penis and the glanular urethra using the magnetic resonance imaging (MRI) [5]. In vivo images showed that; 1) the male urethra is not a uniform tubular structure and has distinct attachments in the glans penis, 2) the glanular urethra has a wider caliber than the proximal penile urethra, a vertically elliptical shape, resembling a laterally compressed, slit-like passage (fossa navicularis), 3) corpus spongiosum covers the penile urethra and gradually terminates at the mid-glanular level. After that level, extensions of a fibrous tissue (septum glandis) are seen around the fossa navicularis, 4) the major components of the septum glandis are observed as dense fibrous tissue at the upper and lower borders of the fossa navicularis, which holds the glanular urethra in the midline between the corpus cavernosum and the

☆ This study is presented at the 3rd Hypospadias World Congress, Philadelphia, U.S.A., 30.10.2019-1.11.2019

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https://doi.org/10.1016/j.mehy.2020.109642
Received 28 January 2020; Accepted 25 February 2020
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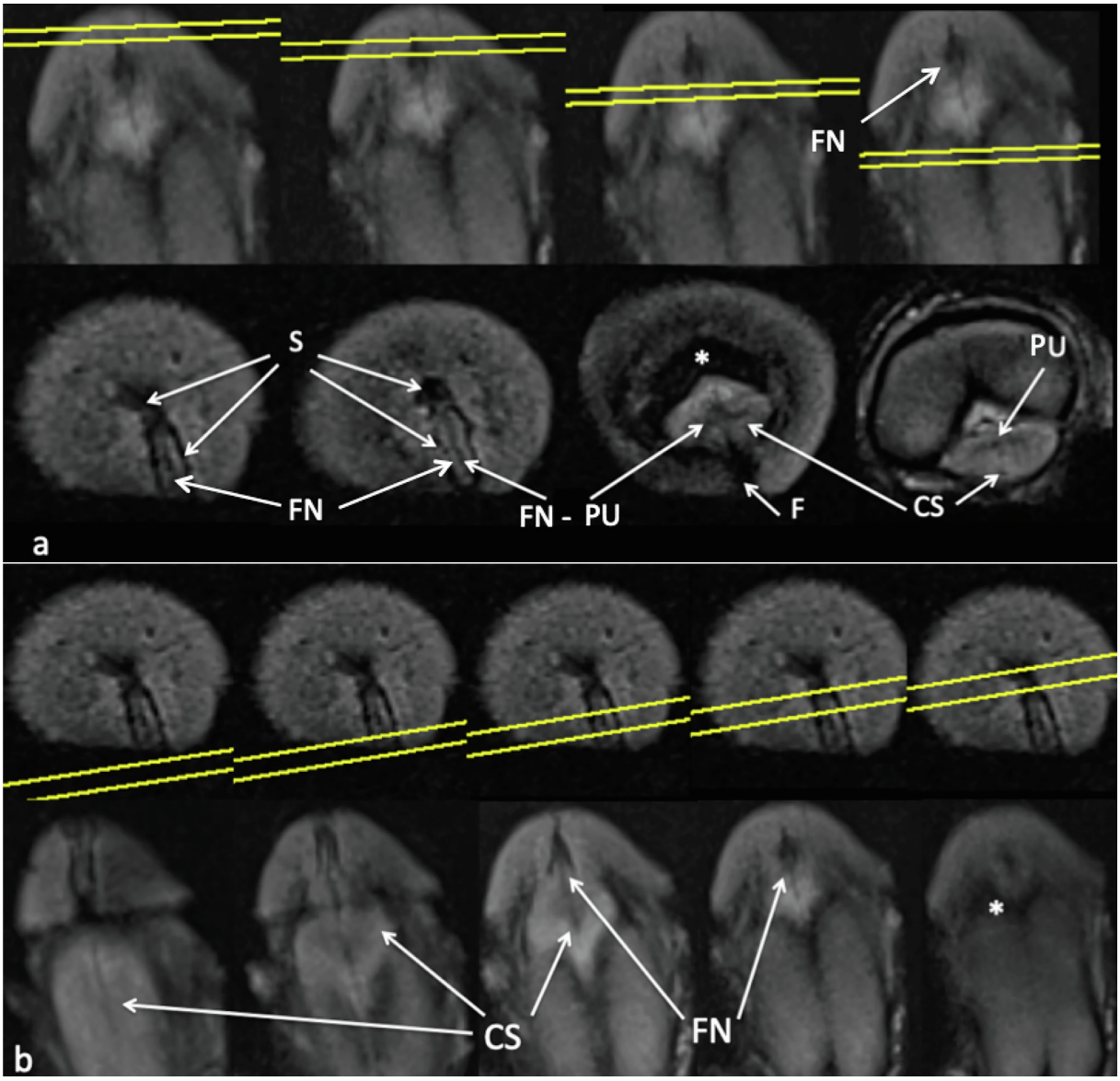

Fig. 1. a&b) MR images of the glans penis showing the structural details of the glanular urethra (fossa navicularis) and its connections. Note the changes in the configuration of the urethra at the level of glans penis. Septum glandis (S), frenulum (F), penile urethra (PU), fossa navicularis (FN), corpus spongiosum (CS), and the ligamentous component of the septum glandis (*).

frenulum, and 5) glans wings are separated ventrally by the septum glandis and frenulum (Fig. 1a&b). Recent studies showed that the urethral development within the glans penis occurs via an entirely different mechanism from that in the penile shaft. In contrast to the penile shaft, direct canalization of the glanular urethra takes place within the human glans without forming a groove [4]. We propose that the penile and glanular urethra have different dynamics of the urine flow, since they have different shapes and structural properties with different embryological development. We mathematically modeled the flow of urine and analyzed the flow dynamics in this particular zone of the urethra.

Empirical evidence

The dynamics of urine flow in the penile and glanular urethra can be explained with the basic principles of fluid mechanics. Integral average equations are used as alternatives to detailed analytical or numerical solutions for the conservation of mass and linear momentum rather than using the differential forms of conservation relations. The two major principles of fluid mechanics, the “Bernoulli’s principle” and the “continuity of flow principle”, provide a sufficient understanding for our suggestion. The continuity of flow (conservation of mass) principle is derived from the fact that the mean velocities at all cross sections having equal areas are equal, and if the areas are not equal, the velocities are inversely proportional to the areas of the respective cross sections. The Bernoulli’s equation states that a decrease in the velocity of a fluid occurs simultaneously with an increase in pressure. As it is a steady laminar flow in an expanding channel, Bernoulli’s Equation is applied as the conservation of linear momentum for urine flow in the male urethra [12]. Since urine is assumed as an incompressible and Newtonian fluid, the simplified form of Bernoulli’s Equation neglecting the frictional force is described as follows [11,13]:

$$\frac{\rho}{2}dv^2 + dp + \rho g dz = 0 \quad (1)$$

(ρ: fluid density, v: fluid velocity, p: fluid pressure, g:gravitational acceleration, z: height)

The integrated form of Bernoulli’s Equation is highly useful in

characterizing velocity in various fluid flow situations. The constant of integration is different for each streamline. Viscous losses are significant near solid surfaces where velocity gradients are large. In addition, viscous losses are significant when the flow conditions dramatically change as in expansions, contractions or branches. When the changes are gradual, viscous losses are minimal, and Bernoulli's Equation is applied [12]. The integrated form of equation [1] is:

$$\frac{1}{2}\rho v^2 + p + \rho g z = constant \tag{2}$$

Since the urine flow is on the centerline of the urethra and no vertical change is detected, the gravity can be neglected. A gradual structural expansion of the urethra (fossa navicularis) occurs within the glans penis, therefore, no recirculation of the flow would be expected. The simplified form of the equation with no gravity term is:

$$\frac{\rho}{2} dv^2 = -dp \tag{3}$$

and

$$v_1 A_1 = v_2 A_2 \tag{4}$$

According to the law of mass conservation, Eq. (4) can be applied for the urethra and the fossa navicularis. A_1 and A_2 are cross sectional areas of the urethra and the fossa navicularis respectively, and v_1 and v_2 are the urine flow velocities of these locations (Fig. 2a). According to the conservation of mass law, the integrated form of equation (3) is as follows:

$$\frac{\rho}{2}({v_1}^2 - {v_2}^2) = p_2 - p_1 \tag{5}$$

The combination of the Eqs. (4) and (5) is as follows:

$$p_2 = p_1 + \frac{\rho}{2}{v_1}^2\left(1 - \left(\frac{A_1}{A_2}\right)^2\right) \tag{6}$$

p_1 and p_2 are pressure of the urethra and fossa navicularis, respectively. According to the Eq. (4), flow velocity deceleration occurs due to an increase in cross-sectional area and the increase in pressure occurs up to a maximum value with expansion and then slightly decreases with fully developed flow on the flow direction (Eq. (6)). Because the velocity is inversely proportional to the cross-sectional area A_2, and the pressure is proportional to the inverse square of cross-sectional area A_2. To summarize, the increase in pressure occurs with urethral expansion to fossa navicularis, with neglected frictional and gravitational forces. Therefore, the urine flow is expected to exit the urethra with a pressure higher than the urethral pressure proximal to the fossa navicularis and at a slower rate.

According to the basic principles of fluid dynamics, the glanular urethra where it forms the fossa navicularis has important effects on the flow dynamics and shape of the urine exiting the urethra. For a steady incompressible flow through a tube, the hydraulic resistance of the tube depends on the cross-sectional shape of the tube. The results of the velocity field studies show lower velocity loss at the major axis, than the minor axis in a tube with elliptical cross-sectional shape [14] (Fig. 2b). Transformation of the urethra into a navicular and vertical elliptical shape should lead to an increase in pressure and changes in the velocity gradient. In the glanular urethra, the major axis correlates with the diameter between the upper and lower corners, while the minor axis correlates with the diameter between the sidewalls of the fossa navicularis. Therefore, the flow of urine on the sidewalls of the fossa navicularis shows a higher velocity loss than at the upper and lower corners. This should be the reason for the wave-like shape of the urine exiting form the urethra, since the streams emerging from the major and minor axis of the fossa navicularis meet at higher and lower flow velocities at a certain distance from the meatus. High surface tension on the major axis and increased surface displacement on the minor axis of the fossa navicularis and external urethral meatus are most likely provided by the septum glandis, resulting in an elastic, slit-like configuration.

Discussion

The glanular urethra is ventrally covered by the distalward growth of the prepuce, with its median primordial fascial tissues forming a septum (septum glandis) and the frenulum. The glans wings do not fuse on the ventral midline, and the septum glandis and the frenulum are included in the formation of the distal (glanular and subcoronal) urethra and its ventral wall [15–19]. Dr Friedrich Gustav Jacob Henle (1809–1885) was first to describe "septum glandis" as a median fibrous tissue surrounding the fossa navicularis [2]. Corpus spongiosum, both in his drawings and in our MRI study, was detected to gradually terminate at the mid-glanular level where it meets the largest diameter of the fossa navicularis (Fig. 3). The fossa navicularis is surrounded by a fine layer of fibers, which emanates from the septum glandis. This fibrous layer distally dissolves into individual bars around the urethral orifice and divides the glans into outer and inner layers [3,6]. Our

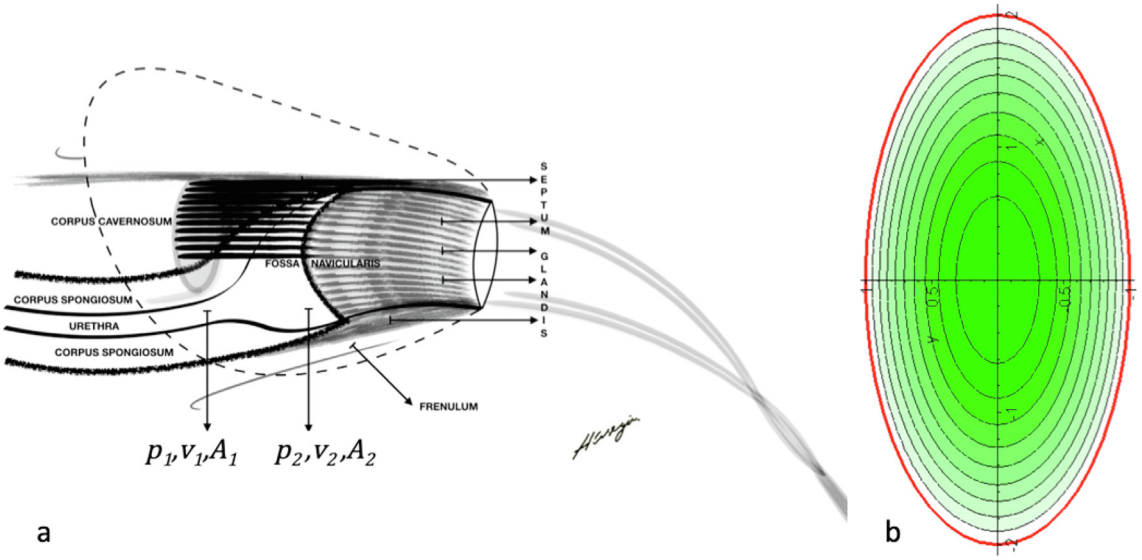

Fig. 2. a&b: a) The changes in the configuration and the cross-sectional area of the proximal (A_1) and glanular urethra (A_2), with pressure (p) and velocity (v) changes in urine flow. b) Velocity contours in an elliptical tube, showing lower velocity losses at the major axis (with kind permission of Dr J Lekner).

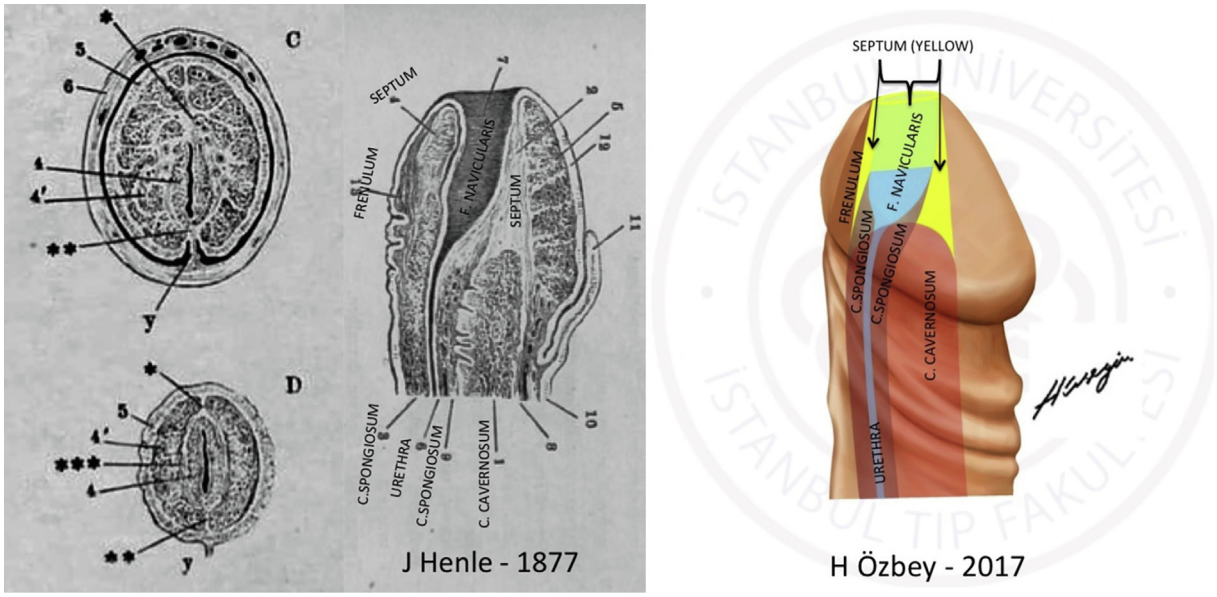

Fig. 3. Cross sections of the glans penis showing fibrous tissue (septum glandis) surrounding the fossa navicularis (***). Note the gradual termination of the corpus spongiosum at the mid-glanular level and its replacement by the septum glandis. The upper (*) and lower (**) median septum, and frenulum (y) (Henle). B) Schematic description of the glans penis (Özbey).

schematic description of the human glans penis corresponds to the findings of J Henle and to the recent findings obtained by microscopic and scanning electron microscopy and optical projection tomography studies [4,5,20,21]. Henle's "septum glandis", connecting the distal ends of the two corpora cavernosa with the glans penis is also called as "distal ligament" and "corporo-glans ligament" [22,25]. The macroscopic and microscopic morphological features of this central ligamentous tissue penetrating the human glans penis by the course of the fossa navicularis were recently studied. Saggital dissection of penises of formalin-embalmed cadavers showed the presence of a fibrous-ligamentous tissue consisted of centrally integrated collagen bundles and distally with fine elastic fibres, covering the fossa navicularis and urethral meatus [25]. This fibrous tissue is usually considered to contribute to the flexibility and rigidity of the human glans penis, in particular during penile thrusting [23,25]. These anatomical details show that compliance of the glanular urethra must be different than of the proximal penile urethra, which may play a role in controlling the flow of the urine exiting the urethra. Our MRI findings demonstrated that the fossa navicularis and the meatus have a slit-like form at rest. The mechanical behavior of the urethra has a close relationship with its physiological function during micturition. The adaptive configuration of the fossa navicularis and the meatus during micturition is most likely provided by the fibro-elastic septum glandis.

The biophysics behind the characteristic shape or wave pattern made by the urine stream as it exits the urethral meatus has been studied with a computational fluid dynamics model [26]. The shape of a liquid stream exiting from an elliptical orifice such as urethral meatus was reported to be associated with the flow rate, orifice size and geometry, affected by the surface tension and surface displacement. However, the researchers have not considered the shape and the structural properties of the fossa navicularis. The navicular configuration of the glanular urethra and its attachments within the glans penis are important on urine flow dynamics in addition to the orifice size and geometry. The support of the surrounding tissues (corpus spongiosum and tunica albuginea) are supposed to influence the mechanical behavior of the male urethra such as deformation, stress and strain [24,27,28]. According to fluid dynamics, the gradual disruption of the corpus spongiosum at the level of glans penis, its replacement by a thin layer of fibrous tissue (septum glandis), along with urethral configuration change, should result in changes in the compliance and flow characteristics (pressure and velocity) of the urine. We suggest that the volumetric form, velocity changes and the wave-like shape of the urine flow are provided by the fossa navicularis that is surrounded by the septum glandis. Since they regulate the flow characteristics of the urine, we conclude that the fossa navicularis and the septum glandis play a functional role as a "flow control chamber" of the male urethra.

A normal looking, straight penis and a vertical, slit-like meatus with a "well-approximated glans" are suggested as to be the main aims in hypospadias repair [29,30]. In almost all hypospadias repair techniques, the urethra has always been reconstructed as a uniform tube over a catheter or stent, and the fossa navicularis has always been neglected. The septum glandis and the frenulum were also always neglected and the glans wings are dissected and approximated to enclose the neo-urethra. However, the male urethra is not a tubular structure with uniform configuration and diameter by forming the fossa navicularis in the glans penis [31–33]. In addition, meatal stenosis, fistula and pathologic uroflow pattern are the major complications of urethroplasties in hypospadias, which may reach a rate of up to 25% [7,29,30,34,35]. The obstructed flow at uroflowmetry is related to meatal stenosis or as a result of a non-compliant neo-urethra [8,30,34]. Signs and symptoms of persistent obstructive voiding are referred to as "functional obstruction of the neo-urethra" despite successful calibration or dilation [35]. As we show, the glanular urethra is not covered over its entire length by the glans tissue, but supported ventrally by the septum glandis and the frenulum. We believe that the exclusion of these anatomical features of the glanular urethra for decades has led to many misconceptions and false suggestions in hypospadias surgery.

In conclusion, the male urethra is not a uniform tubular structure. The fossa navicularis, which is surrounded by the septum glandis, causes changes in the boundary force and configuration of the urethra, which leads to changes in the pressure and velocity of urine flow. It can be said that the fossa navicularis and septum glandis play a role as 'flow control chamber" in controlling the flow of the urine exiting the urethra.

Conflict of interest statement

No conflict of interest

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.mehy.2020.109642.

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