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·*Clinical Experience*·

Hypothesis of human penile anatomy, erection hemodynamics and their clinical applications

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Abstract

Aim: To summarize recent advances in human penile anatomy, hemodynamics and their clinical applications. **Methods:** Using dissecting, light, scanning and transmission electron microscopy the fibroskeleton structure, penile venous vasculature, the relationship of the architecture between the skeletal and smooth muscles, and erection hemodynamics were studied on human cadaveric penises and clinical patients over a period of 10 years. **Results:** The tunica albuginea of the corpora cavernosa is a bi-layered structure with inner circular and outer longitudinal collagen bundles. Although there is no bone in the human glans, a strong equivalent distal ligament acts as a trunk of the glans penis. A guaranteed method of local anesthesia for penile surgeries and a tunical surgery was developed accordingly. On the venous vasculature it is elucidated that a deep dorsal vein, a couple of cavernosal veins and two pairs of para-arterial veins are located between the Buck's fascia and the tunica albuginea. Furthermore, a hemodynamic study suggests that a fully rigid erection may depend upon the drainage veins as well, rather than just the intracavernosal smooth muscle. It is believed that penile venous surgery deserves another look, and that it may be meaningful if thoroughly and carefully performed. Accordingly, a penile venous surgery was developed. **Conclusion:** Using this new insight into penile anatomy and physiology, exact penile curvature correction, refined penile implants and promising penile venous surgery, as well as a venous patch, for treating Peyronie's deformity might be performed under pure local anesthesia on an outpatient basis. *(Asian J Androl 2006 Mar; 8: 225–234)*

Keywords: penile venous anatomy; curvature correction; penile venous surgery; tunica albuginea; distal ligament; deep dorsal vein; cavernosal vein; para-arterial vein; ischiocavernosus; bulbospongiosus

1 Introduction

The human penis is a unique structure composed of multiple fascial layers which surround the three cylinders of erectile sinusoids. Thus, it consists of the glans penis, the corpus spongiosum with the bulb of the urethra, the paired corpora cavernosa and the bulbospongiosus, as well as the ischiocavernosus muscles [1]. If no venous leakage exists, the sinusoid of the corpora cavernosa is the most ideal milieu in which to apply Pascal's principle [2], which depicts that pressure applied to any part of the enclosed fluid at rest is transmitted undiminished to every portion of the fluid and to the walls of the containing vessel in the entire human body. It has been widely studied and is generally agreed that its anatomy is well-established. The tunica albuginea is, however, consis-

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tently described as a single layer with uniform circumferential thickness and strength [3]. The bone penis is not indispensable to every mammalian species, and it is commonly admired and believed that there is a complete loss of bone penis in human beings and that only glanular sinusoids have been described. Should, therefore, the glans penis be too weak to bear the buckling pressure generated from coitus? On the penile venous vasculature, a single deep dorsal vein is consistently depicted between the tunica albuginea and the Buck's fascia, and is regarded as an exclusive exception in that the ratio of the number of arteries to veins is 1:2 in the entire human body, although two circulatory routes within the corpus cavernosum are described [4]. Furthermore, the relationship between the outer layer of the tunica albuginea and the bulbospongiosus, as well as the ischiocavernosus muscles, is not clear. Similarly, the relationship between the skeletal and the smooth muscle has never been clearly described.

Although remarkable advances have been made in our knowledge of penile pathophysiology for erectile dysfunction (ED) over the last decade, from which treatment modalities derive [5], these, however, were unequivocally based on a traditionally-described anatomy which shall be called into question [6]. As an andrologist, there are some events in our daily practice which may indicate to us that the penile anatomy, as described in published works, may not be absolutely correct, and neither the treating strategy for ED. In 1985, an impotent patient asked me whether the bony ridge that he palpated inside his glans penis from the urethral tip was an abnormal growth. In his heart, this patient had long yearned for a cure for his intractable impotence. He ascribed his awkward disease to this structure which has not been identified in the literature. This question remained unanswered until it was proven to be a normal structure named the distal ligament [7]. I realized then that we should question our basic knowledge of the wonderful organ which is an emblem of androides.

Similarly, the present consensus [8] seems to disregard the venous factor as a contributor to ED, and prefers the cavernosal factor along with hormonal deficiency, arterial insufficiency, neurological disease, adverse effects from drugs, chronic systemic diseases, and the psychogenic factor, such as etiologic contributors. But, should the venous factor be included? Our recent study on seven fresh cadaveric penises disclosed that a fully rigid erection was unexceptionally attainable once their erection-related veins were removed [9]. All of these innovative findings of the penile anatomy, as well as physiology, are attributable to the works of a researcher who is a clinical surgeon rather than a basic science researcher, such as an anatomist. Thus, this anatomical knowledge as well as new insights into erection could be helpful in guiding clinical works. I would like, therefore, to review the recent advances on the human penile anatomy, the hemodynamic phenomenon of penile erection as well as their clinical applications.

2 Subjects and methods

From June 1992 to December 2003, a total of 65 human male cadavers with intact penises were used for a series of studies. These studies were inspired by information from clinical patients and were compared with that from murine as well as canine penises. Using dissecting microscopy, light microscopy, scanning transmission electron microscopy as well as cavernosography clinically, the fibroskeleton structure, penile venous vasculature and the relationship of the architecture between skeletal and smooth muscles were studied. All tissue blocks were stained with hematoxylin and eosin, alcian blue, periodic acid Schiff, Masson trichrome, Victoria blue, Picrosirius red stain and Hart or orcein stain, as necessary, and examined under light microscopy with or without polarizing microscopy.

3 Results and discussion

3.1 Penile anatomy

3.1.1 The fibroskeleton: tunica albuginea and its relevant fibroskeleton

The tunica albuginea [7] of the corpora cavernosa is a bi-layered structure with which the collagen bundles of the inner layer are arranged circumferentially and those of the outer layer are arrayed longitudinally (Figure1). The inner layer completely contains and, together with the intracavernosal pillars, supports the sinusoids. There is a paucity of outer layer bundles, resulting in a weak sector which may be susceptible to surgical trauma during penile implant [10], at the region between the clockwise 5 and 7 o'clock positions, where there are two triangular ligament structures. These structures, termed the ventral thickening, are a continuation of the left and right bulbospongiosus muscles. There is close contact between the corpora cavernosa and the corpus spongio-

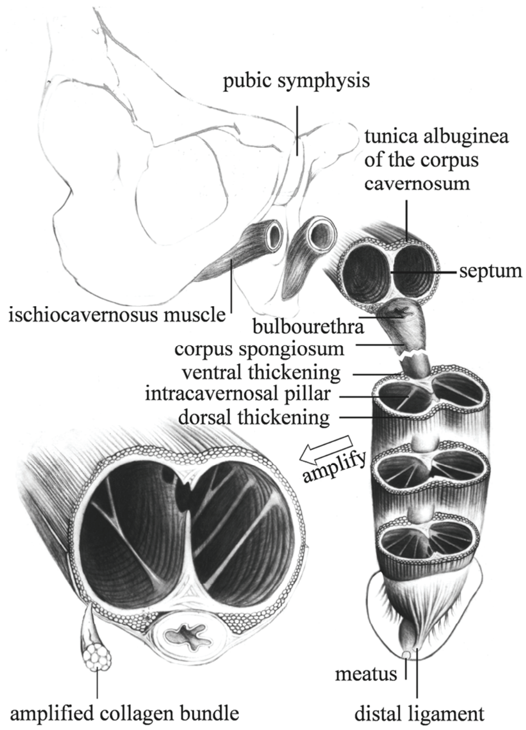

Figure 1. Schematic illustration of the fibroskeleton in the human penis. The tunica albuginea of the corpora cavernosa is a bi-layered structure. The inner circular layer completely contains and, together with the intracavernosal pillars, supports the sinusoids. There is a paucity of outer layer bundles at the region between the 5- and 7-o'clock positions where there is close contact with the corpus spongiosum. Distally, they are grouped into the glans penis forming the distal ligament, located at the 12-o'clock position of the distal urethra. The median septum is incomplete with dorsal fenestration at the pendulous portion of the penis and merely complete where the penile crura are nearly formed.

sum. On the dorsal aspect, between the 11 and 1 o'clock positions, there is again a dorsal thickening of the outer longitudinal tunica, a radiating aspect of the bilateral ischiocavernosus muscles. Distally they are grouped into the glans penis, forming the distal ligament, an indispensable continuation of the outer longitudinal layer of the tunica located at the 12 o'clock position of the distal urethra. It is arranged centrally, and acts as a trunk of the glans penis. The median septum is incomplete with dorsal fenestration at the pendulous portion of the penis, which is diverged so widely from that depicted in the traditional textbook. Its amount of fenestration is commensurate with the quantity of the intracavernosal pillars. Thus, at a distal penis, the pillars are numerous where the septum is most incomplete, in order to allow for the tensile capability.

The tunica albuginea had been consistently described as a single layer with uniform circumferential thickness. It is, however, unequivocally a bi-layered structure in which the outer longitudinal layer can be regarded as a tendon-like tissue of the finger in the extremities. Thus, it is indeed a continuing structure of the skeletal muscles positioned proximally. The two-layered design is functionally similar to that of a bicycle's tire, where the inner tire is responsible for confining the inflated air (blood in a sinusoid of the penis), and the outer tire is responsible for supplying strength. It is, therefore, a bi-layered tunica which can meet the requirement for rigid erection. This anatomical knowledge is deemed to be a prerequisite for clinical surgeons who attempt to perform surgeries on the delicate tunica albuginea.

The distal ligament of the glans penis has been overlooked in our published reports. This unique anatomical arrangement may explain why the glans penis is strong enough to bear the buckling pressure of coitus, as well as how an erect penis is sufficiently rigid but never compresses the corpus spongiosum, which, otherwise, would present an obstacle to ejaculation. Without this strong ligament, it would be like a Christmas tree without a trunk and an umbrella without a stick. A detailed comprehension of the penile anatomy is, therefore, certainly meaningful, and could provide a further foundation for penile surgical techniques and methods.

3.1.2 Penile venous anatomy

The deep dorsal vein (Figure 2), consistently in the median position, receives blood from the emissary veins, which are the exits of the subtunical venular plexus from the corpora cavernosa, and of the circumflex vein from the corpus spongiosum [11]. It is sandwiched in by cavernosal veins, although these lie in a deeper position. Bilaterally, each dorsal artery is sandwiched in by its corresponding medial and lateral para-arterial veins. A sagged-positioned communicating vein (Figure 3A, B) is clearly seen between the two, and acts as a hammock to the corresponding dorsal artery. The lateral para-arterial vein merges with the medial one proximally. The number of the veins between the tunica albuginea and the Buck's fascia in the pendulous portion of the penis is seven, rather than that of the traditionally described one, although it becomes four at the level of penile hilum because a merger takes place in each pair of the nomenclature veins. The erection-related veins are arrayed in an

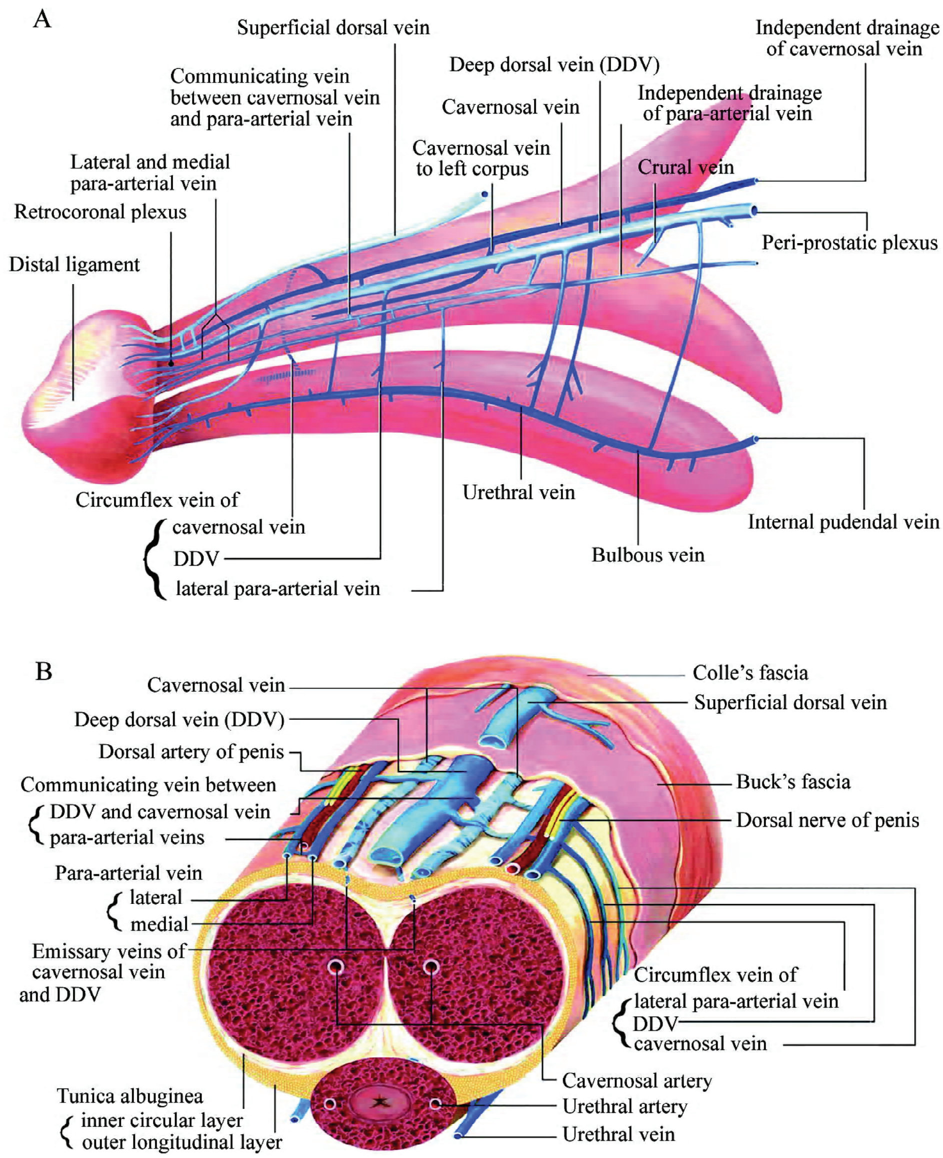

Figure 2. Schematic illustration showing the erection-related vein in the human penis. (A): Lateral view: the deep dorsal vein consistently in the median position, receives the blood of the emissary veins from the corpora cavernosa and of the circumflex vein from the corpus spongiosum. It is sandwiched in by cavernosal veins, although these lie in a deeper position. Bilaterally, each dorsal artery is sandwiched in by its corresponding medial and lateral para-arterial veins. Note that the lateral para-arterial vein merges with the medial one proximally. The deeper color of the veins indicates the deepest group of the vasculature. (B): Cross-section of the mid-portion. Note that the number of veins is seven rather than the one traditionally described, although it becomes four at the level of penile hilum because a mergence takes place in each pair of the nomenclature veins. The erection-related veins are arrayed in an imaginary arc on the dorsal aspect of the tunica albuginea. (This photo was reproduced from Hsu *et al.*[11], with permission.)

imaginary arc on the dorsal aspect of the corpora cavernosa. The relationship of the vasculature to the fibroskeleton is interesting and the difference of penile venous and arterial vasculature is substantial. The veins traverse in an oblique path between the inner and the outer layers of the tunica albuginea, whereas the arteries take a more direct route. It is, therefore, not uncommon to see twin tunnels (Figure 3C) in one venous chamber in a cross-section of the penile shaft. It is important to know that not only the deep dorsal vein but

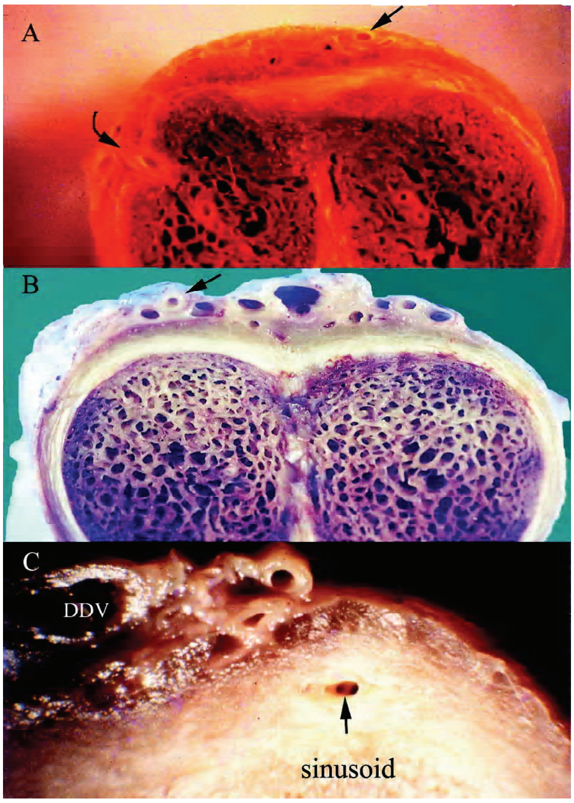

Figure 3. Photographs of the relationship between the vasculature and the fibrous skeleton in the human penis. (A): The artery takes a direct route (cured arrow) to pass the tunica. Interestingly, a sagged-positioned communication is clearly seen between the two and acts as a hammock to the left and right. (B): Dorsal artery (arrows). (C): The venous vasculature traverse the tunica in an oblique path between the inner and the outer layers of the tunica albuginea, therefore, it is not uncommon to see twin tunnels in one venous chamber (arrow) in a cross-section of the penile distal shaft. Note the configuration of the deep dorsal vein (DDV) and the sinusoids of the corpora cavernosa.

also the cavernosal veins, as well as the para-arterial veins, have their own emissary veins.

Traditionally, a single deep dorsal vein is depicted between the tunica and the Buck's fascia. However, erection-related veins are introduced because, other than the common drainage, each of the three cylinders has its own corresponding vein. Hence, in a human body, it is a rule that the number of the veins is normally greater than the number of the arteries. The penile venous vasculature has been consistently described as the superficial, the intermediate and the deep. The last one is exclusively limited in the penile hilum. However, the cavernosal veins ought to be noted and extended to the glanular level. Thus, one more storey-like configuration of deep veins between the tunica albuginea and the imaginary arc of the deep dorsal vein and the dorsal arteries, which are sandwiched in by their own para-arterial veins bilaterally, ought to be added. The microdissection and complete study of penile venous vasculature can be attainable when a knowledge of erection-related veins is a prerequisite through the imaging of cavernosograms, as well as the information from penile venous surgery. A complete tracing of the venous tissue is impossible otherwise, as it is fragile and can easily be ruined after immersion in formalin. Thus, the hypothesis that independent multiple veins, rather than a single deep dorsal vein, in the human penis is initially derived from the sustained experience of handling penile venous surgery [11].

Not surprisingly it is not difficult to leave a "residual vein" which, in turn, is described as a "recurrent vein" if a postoperative result is disappointing when venous surgery is attempted.

3.1.3 Relationship between skeletal muscles and smooth muscles

In the human penis, the smooth muscle structure is found inside the vascular walls and the sinusoidal walls which are intertwiningly formed with the smooth muscle cells and the fibrous tissue structures wherever in the glans penis, the single corpus spongiosum, and the paired corpora cavernosa. The components of the skeletal muscles include the ischiocavernosus muscle, the bulbospongiosus muscle, and their continuation structure (Figure 4). The tunica albuginea is, however, distributed exclusively, depending upon the specifically functional requirement of each anatomical component [12]. Thus, the skeletal ischiocavernosus muscle, the bulbospongiosus muscle, and a bi-layered tunica albuginea support and form the corpora cavernosa, the most ideal milieu in the entire human body, to which Pascal's principle can be applied. The skeletal bulbospongiosus muscle and a mono-layered tunica albuginea enclose, partially, the corpus spongiosum, allowing, therefore, ejaculation when erection is rigid. In the glans penis, however, the skeletal distal ligament is entrapped by the smooth muscle sinusoids and serves as a trunk which enables the glans to protect the reflexogenic erectile mechanism, and is essential to coitus.

This muscular integrity is essential in determining whether a penis is healthy or not. Any surgical attempt,

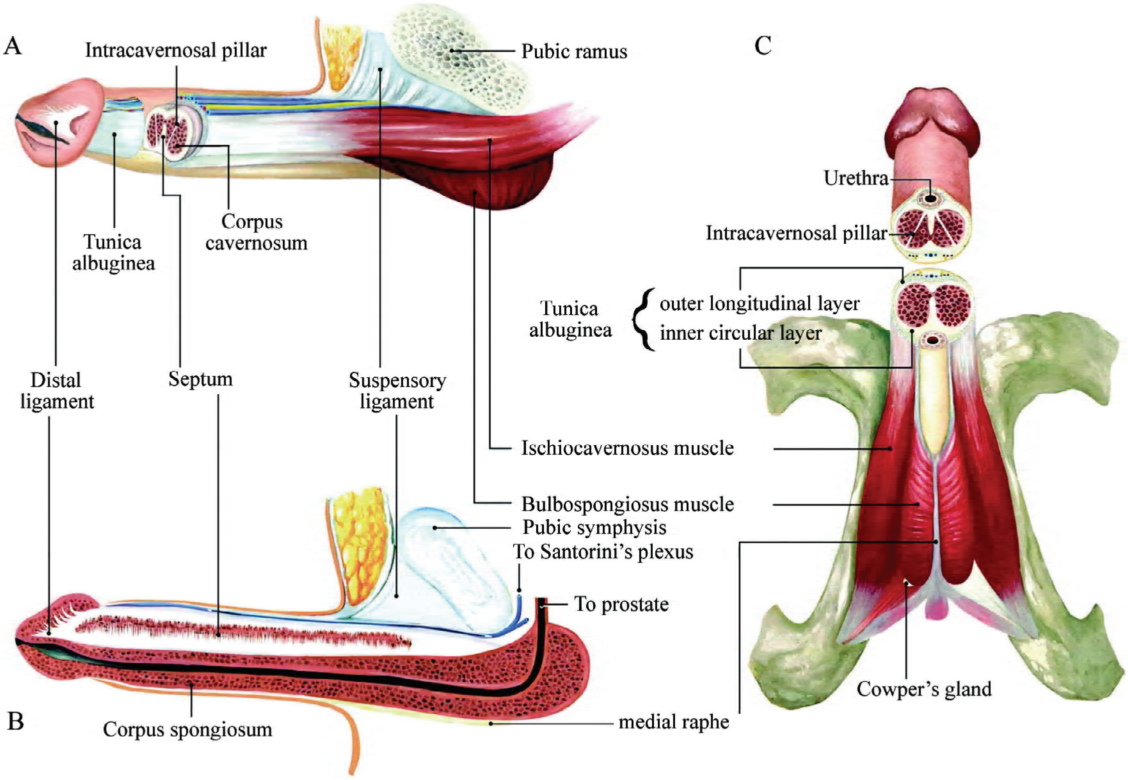

Figure 4. Schematic illustration of the human penis. (A): Lateral view: the penis leans upon the suspensory ligament, which is an extension of the linea alba. Proximally, it is capped by the glans penis and the corpus spongiosum is held by the bulbospongiosus muscle in which the fibers are mostly transverse. The corpora cavernosa are surrounded by a bi-layered tunica albuginea composed of inner circular and outer longitudinal collagen bundles. The intra-cavernosal pillars, which may be considerably more numerous distally, are a continuation of the inner circular layer. The corpus cavernosum is entrapped in the ischiocavernosus muscle with the muscle fibers aligned in the longitudinal arrangements. (B): Medial view: the distal ligament is aggregated from the collagen bundles of the outer longitudinal layer of the tunica albuginea. It is an inelastic fibrous structure which forms the trunk of the glans penis. The incomplete septum is dorsally fenestrated. The corpus spongiosum contains the urethra. (C): Ventral aspect: the 3-D structure of the human penis is evident. The ischiocavernosus muscle is paired and situated at the lateral boundary of the perineum. Each segment covers its ipsilateral penile crus. The anterior fibers of the bulbospongiosus muscle partially spread out to encircle the corpus cavernosum (not shown) and mostly insert into the ventral thickening of the tunica. (This photo was reproduced Hsu *et al.* [12], with permission.)

if erection is a concern, should be muscle sparing. If anatomical knowledge is deemed a prerequisite for any surgeon, local anesthesia for a penile implant and venous patch surgery should be delicately managed and irreversibe iatrogenic damage of the muscles resulting from crural detachment or ligation can be avoided. This situation is similar to that of a freely movable finger, which can only be preserved if the arm-sited muscle is aware of being saved during an attempted hand surgery.

3.2 Pathophysiology of ED

The present consensus of the pathophysiology is that ED is due to the cavernosal factor, that an inability to achieve or sustain a sufficiently rigid erection is attributed to the loss of smooth muscle relaxation, that fibrous compliance results from a defect in the regulation of collagen synthesis and degradation as a result of an abnormality in the transforming growth factor-β1 (TGF-β1), most likely secondary to chronic ischemia [8]. Therefore, the accepted theory is that ED should be attributed to a hormonal deficiency, arterial insufficiency, neurological impairment, adverse reaction to drugs, systemic chronic disease, psychological disturbance, and cavernosal defect ("hands PC" is the acronym produced by taking the first letter of each contributing factor). However, we recently conducted a hemodynamic study on seven fresh human cadavers and found that reaching a rigid erection was unequivocally attainable after the erection-related veins in all subjects were removed, in spite of the fact that their sinusoidal tissues were not alive [9]. This implies that a full-rigid erection may depend upon the drainage veins as well, rather than just the intracavernosal smooth muscle. We might elucidate that the mechanism of erection is also a matter of the vascular phenomenon of hemodynamics. Thus, a fully rigid erection may be independent of an intracavernosal factor, such as the TGF-β1. Does it mean that their TGF-β1 does not contribute much to their awkward ED? The introduction of sildenafil, the first clinically available agent in the family of phosphodiesterase-5 inhibitors, its mechanism, is well recognized for its ability to increase the blood inflow, and in turn, the amount of blood drainage will be markedly hampered. Does this mean that there exists a disassociation between the effective agent and the underlying cause of ED, as sildenafil is neither a reverser nor a modulator of the TGF-β1? Further scientific studies should be conducted to clarify this dilemma. Overall, a rigid erection depends on cooperating healthy sinusoids, normal tunica, functional artery and the veno-occlusive function. Thereafter, it is our opinion that the "veno-occlusion factor" might be included and ought to be imposed over the cavernosal factor. This would mean that "hands PC" would be changed to "VP hands", very potent hands.

3.3 Clinical applications

3.3.1 Penile curvature correction

A curvature is a result of a discrepancy in the surface area of the corpora cavernosa where it is bisected from the best symmetrical plane. A perfect surgical correction is challenging and may be indicated for those with a deformed penis which prevents them from performing normal coitus. A variety of surgical modalities has been introduced in an attempt to model the ideal shape and this is well described [13]. The available methods include the Nesbit's procedure and tunical placation. It is agreed, however, that resumption of its curvature associated with reduced erectile capability is one of its unavoidable complications, which is commonly ascribed to the suture material of being too weak to hold the tunica. It is, therefore, advisable that a strong suture material such as 2-0 or 3-0 nylon should be used for this purpose.

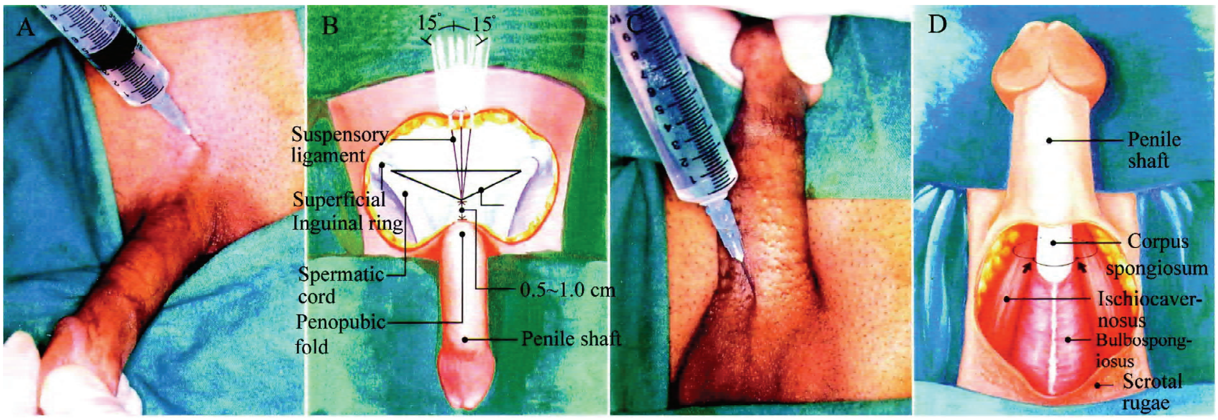

Figure 5. Photographs and illustration of regional block. The patient is put in the supine position which is suitable for the entire operation. (A): Proximal dorsal nerve block, the needle, with its bevel parallel to the direction of the body axis, was quickly inserted 0.5–1.0 cm cranial to the penopubic fold in between the suspensory ligament until the infrapubic angle was met. (B): Illustration of the precise positions injected. It was injected in three directions, medially and 15° obliquely and bilaterally, in the penile hilum in order to cover the bilateral dorsal nerves. (C): Ventral infiltration. The peripenile space is meticulously infiltrated one-and-a-half finger-breadths below the penoscrotal junction using finger-guided manipulation, in which the index finger of the assistant's hand is used to confirm the precise position of the injection. (D): Illustration of its anatomical landmarks. The peripenile injection should be made to encircle the penile shaft. Note that the junction between the corpus spongiosum and the corpora cavernosal (arrow), that is, at the 5- and 7-o'clock positions, should be exactly blocked, otherwise an incomplete blockage will be unavoidable. Subsequently, the needle is withdrawn and advanced laterally to inject the lateral aspect of each corresponding crus. (This photo was reproduced from Hsu *et al.* [14], with permission.)

According to our study, a proper repair of the collagen bundles of the outer layer tunica is the determinant of surgical success regardless of the strength of the suture used. This viewpoint is meaningful, either a simple Nesbit's procedure or a venous patch is needed for the correction of a Peyronie's deformity.

3.3.2 Penile implant

Although the introduction of sildenafil has significantly changed the therapeutic modalities in patients with ED, penile implantation still remains the final solution for some patients with a refractory erectile problem. A method of regional blockage [14] in which a proximal dorsal nerve block, peripenile infiltration (Figure 5) and crural block was introduced based on the knowledge of the delicately anatomical structure of the human penis [15]. This block not only offers a desirable option of local anesthesia for penile implantation but can also avoid the inadvertent traumatization of the most vulnerable anatomical region and, in turn, can minimize the susceptibility of complications.

3.3.3 Penile venous surgery

A longitudinal pubic incision (Figure 6A) is made and the pendulous portion of the penis is then released with an inside-out maneuver (Figure 6B). ubsequently, the deep dorsal vein system is thoroughly stripped with a pull-through maneuver and ligated using 6-0 nylon. It is advised that the Buck's fascia is to be intermittently opened over the exit of the emissary/circum-

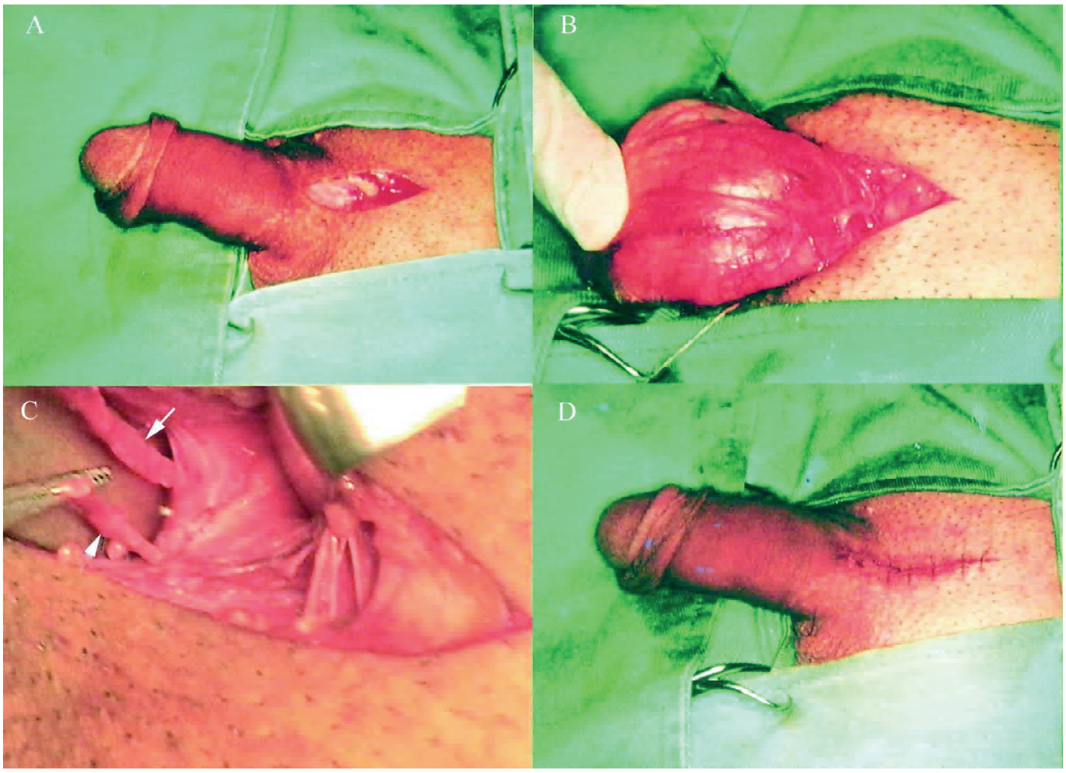

Figure 6. Photographs of venous stripping surgery. (A): A longitudinal pubic incision, 1.5 times as long as the diameter of the proximal penile shaft, is carefully made. (B): An inside-out maneuver is meticulously performed, sufficient to release the pendulous portion of the penis. A milking manipulation (squeeze the sinusoids and related veins) will enhance the visibility of the vein. The stripping procedure must be complete until the retrocoronal plexus, where up to several dozen veinlets can be seen. A pull-through technique (usually required five times) is applied proximally to strip the venous tissue in the pendulous penis. (C): After the penis is reduced back to its original position, the trunk of the deep dorsal vein (arrow) as well as the cavernosal vein (arrowhead) serves as a guide to strip the venous plexus until the arcuate ligament while 8–15 tributary veins are managed. (D): The wound is closed with 5-0 catgut or 6-0 nylon sutures while the penile shaft is stretched as much as possible by an assistant's hand. Finally, a compression dressing is placed to encircle the penile shaft, which is similarly stretched.

flex vein to the deep dorsal vein as it is dissected along the shaft instead of a continuous opening. The trunk of the vein is subsequently passed from opening to opening to minimize tissue damage during the entire venous stripping. It is made step-by-step, with the trunk of the deep dorsal vein serving as a guide and likewise the cavernosal veins. The suspensory ligament is separated medially proximal until the level of the infrapubic angle is encountered. The para-arterial veins are managed segmentally. In our experience, a total of 76–125 ligature sites are required to complete the entire procedure (Figure 6C). Finally, the wound is closed with 5-0 catgut or 6-0 nylon suture (Figure 6D) while the penis is stretched as much as possible by an assistant's hand.

Surgery on the deep dorsal vein for atonic impotence was advocated as early as almost a century ago [16]. However, because of the discouraging results [17], this surgery is very rarely indicated and should only be performed on highly selected patients. Although there have been a large variety of techniques described attempting to enhance the veno-occclusive mechanism, they uniformly caused significant injury to the integrity of the skeletal muscle, as well as damage to the cavernosal smooth muscle and thermal cautery damage [18]. Nonetheless, under sustained experience based on this anatomical knowledge as well as a refined surgical drill, we used a modified penile venous stripping procedure that is microscopically manipulated and scrupulously complete, where we not only removed the deep dorsal vein (described traditionally) but also the long-distributed and deep-seated cavernosal veins and para-arterial veins. According to our new venous anatomy we consistently encounter two independent venous trunks (Figure 6C) at the level of the penopubic fold during penile venous surgery. There are 7–9 and 5–11 venous plexus to the deep dorsal vein and cavernosal vein system, respectively, till the infrapubic angle is encountered. It is unexceptionally performed under a pure local anesthesia on a true outpatient basis despite it taking 3–6 h. Neither a Bovie nor a suction apparatus is used in the entire procedure and no damage of the muscular integrity is allowed. This kind of surgery, although challenging, may be worthy of being recommended because it is most likely curable [19, 20] and suitable for most patients, contrary to the commonly-held belief that penile venous surgery will fail in about 2 years. Further scientific study should be carried out to clarify this dilemma as it is beyond controversy.

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