SEXUAL MEDICINE REVIEWS REVIEWS

Current Techniques for the Objective Measures of Erectile Hardness

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ABSTRACT

Introduction: One of the most discussed topics in the urology provider's office is that of the male penile erection. Moreover, this is also a frequent basis for consultation by primary care practitioners. As such, it is essential that urologists are familiar with the various means by which the male erection may be evaluated.

Objectives: This article describes several techniques presently available that may serve to objectively quantify the rigidity and hardness of the male erection. These techniques are meant to bolster information gathered from the patient interview and physical examination to better guide patient management.

Methods: An extensive literature review was performed examining publications in PubMed on this subject, including corresponding contextual literature.

Results: While validated patient questionnaires have been routinely employed, the urologist has many additional means available to uncover the extent of the patient's pathology. Many of these tools are noninvasive techniques that involve virtually no risk to the patient and take advantage of pre-existing physiologic properties of the phallus and its blood supply to estimate corresponding tissue stiffness. Specifically, Virtual Touch Tissue Quantification which precisely quantifies axial and radial rigidity, can provide continuous data on how these forces change over time, thus providing a promising comprehensive assessment.

Conclusion: Quantification of the erection allows for the patient and provider to assess response to therapy, aids the surgeon in choice of appropriate procedure, and guides effective patient counseling regarding expectation management. **Rohrer GE, Premo H, Lentz AC. Current Techniques for the Objective Measures of Erectile Hardness. Sex Med Rev 2022;XX:XXX–XXX.**

Key Words: Erectile dysfunction; Penile hardness; Penile rigidity; Sexual dysfunction; Erection

INTRODUCTION

The male erection is an event commonly discussed in the urologists' clinic, often with attempts to quantify how erect the patient can become when a sexual encounter is desired. Descriptions of the penile erection and attempts at understanding the physiology of erectile dysfunction have dated back to about 2000 BC, where "natural" and "supernatural" etiologies of erectile dysfunction were described on Egyptian papyrus.[1,2] This multifaceted event has been studied and described by the great thinkers Hippocrates, Aristotle, and Leonardo da Vinci.[1] While da Vinci was among the first to propose an interaction with blood flow in the physiology of the penile erection, Ambroise Paré accurately outlined the vascular concept in addition to defining penile anatomy. Following this, Dionis noted the importance of retaining penile blood flow to maintain the erection.[1,2]

Since the 1700s, our understanding of penile anatomy, the physiology of erection, and pathophysiology of erectile dysfunction have dramatically evolved. Specifically, in the last 6 decades, the study of penile hemodynamics has boomed and resulted in much more information in the field of sexual medicine. The use of cavernosography[3] and radiopharmaceutical isotopes[4] began in the 1970s to assess the arterial and venous blood flow of the phallus during the erect state. Just a decade later, color duplex ultrasonography was incorporated into this field of study. Along with improved imaging techniques, there was a simultaneous advancement in understanding the physiology of the male erection on the molecular level.

Beyond the primitive functions of sexual pleasure and propagation of the species, the penile erection also serves as an independent predictor of cardiovascular disease[5] and death.[6] Thus, inquiry regarding erectile function or dysfunction may serve to

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uncover occult cardiovascular disease. Herein, erectile dysfunction has been defined as the consistent and/or recurrent inability to attain and/or maintain an erection sufficient for sexual function.[7] This ailment is of global concern, reportedly affecting more than half of men over the age of 40 years old, according to the Mass Male Aging Study.[8] While this was once thought to be a disease of either psychologic or physiologic insult, it is now understood that erectile dysfunction (ED) is multi-factorial and requires a biopsychosocial approach to management.[9]

AIMS

Beyond ED, several other pathological entities require the practitioner to have the ability to evaluate and quantify a penile erection accurately. Quantification of penile hardness is essential in several scenarios faced by the urologist, such as assessing the efficacy of novel treatments for erectile dysfunction, prior to deciding between surgical treatments for Peyronie's Disease, or for counseling patients prior to a procedure that could result in erectile nerve injury. Thus, objective assessment of the penile erection and the degree of hardness represents an integral component of the urologists' toolbox. The objective of this paper is to provide a contemporary review of available tools to evaluate erectile hardness including validated questionnaires, intracavernosal injection testing, duplex ultrasound, nocturnal penile tumescence testing, axial rigidity assessment with digital inflection Rigidometer, shear wave elastography, virtual touch, near-infrared spectroscopy (NIRS), and photoplethysmography.

METHODS

To conduct this review, a search of English-language literature published on or before May 2021 was performed with use of PubMed. The following key terms such and their combinations were used to find these articles: "quantify," "objective," "penile hardness," "penile erection," "penile tumescence," "validated questionnaire," and "ultrasonography." Forty-six articles were selected for review based on relevance. These studies, along with corresponding supplemental materials, will be presented in this review. The goal of this paper is to present current strategies for quantifying the male erection including validated questionnaires, intra-cavernosal injection combined with penile duplex ultrasound, nocturnal penile tumescence testing with the RigiScan, Digital Inflection Rigidometer, Shear Wave Elastography, Virtual Touch Tissue Quantification, and Near-infrared Spectroscopy with Photoplethysmography.[10]

ANATOMY AND PHYSIOLOGY OF THE PENILE ERECTION

Knowledge of the anatomy and physiology of the penile erection provides an essential foundation in understanding the advancements in quantifying erection. The human phallus consists of 3 cylindrical bodies- 1 ventral corpus spongiosum containing the urethra and 2 paired dorsal corpora cavernosa, which serve as the erectile bodies (Figure 1). The corpora cavernosa are encased in the tunica albuginea, a paired fibrous sheath, and communicate with one another via an incomplete septum between the bodies. The blood supply to the penis arises from the internal pudendal artery, renamed the penile artery, which is the final branch of the anterior division of the internal iliac artery. This vessel gives off 3 named branches: the bulbourethral artery, the cavernosal artery, and the dorsal artery. The bulbourethral artery supplies the corpus spongiosum, urethra, and the glans. The cavernosal artery enters at the hilum and gives off tortuous helicine branches as it travels through the center of each erectile body; these branches dilate and straighten with erection.[2] Lastly, the dorsal artery travels along the dorsum of the penis between the nerve and vein where it supplies the skin and gives off circumflex arteries to supply the corpora.

The penile erection is a psycho-neuro-endo-vascular event whereby sexual stimulation causes the release of neurotransmitters such as nitric oxide, which results in blood accumulation into the sinusoidal spaces of the corpora cavernosa and corpus spongiosum as well as erectile smooth muscle tissue relaxation.[11] As arterial inflow increases, sinusoids engorge, the surrounding tunica expands, and venules within the tunica layers become occluded.[12] This venous compression limits outflow and propagates the erection by maintaining intracavernosal pressure. This pressure gives rise to the radial rigidity of the phallus, which allows it to resist deformation when circumferential pressure is applied such as with compressive vaginal forces. Another essential biomechanical property of the phallus is axial rigidity, a function of erectile tissue mechanical properties and penile geometry, which allows the penis to withstand compact loads such as with intromission and pelvic thrusting.

Another key component of the penile erection is parasympathetic innervation via the cavernous nerves, which are branches of the pelvic plexus, originating from S2 through S4.[2] Conversely, excitation of the sympathetic pathway, originating between T11 and L2, results in detumescence by way of the superior hypogastric nerve plexus to the pelvic plexus via the hypogastric nerve. This overview of key functional anatomy is irrespective of the many other components driving sexual function such as the various brain centers involved in desire and hormonal effects on libido.

MEASURES OF ERECTILE HARDNESS

Validated Questionnaires

The least invasive way by which the practitioner may elicit information regarding erectile hardness is a detailed sexual history and validated questionnaire. In patients with a primary complaint of sexual dysfunction, it is essential to obtain a detailed sexual history to identify what sexual issues might exist, any possible contributing biological and psychological factors, possible

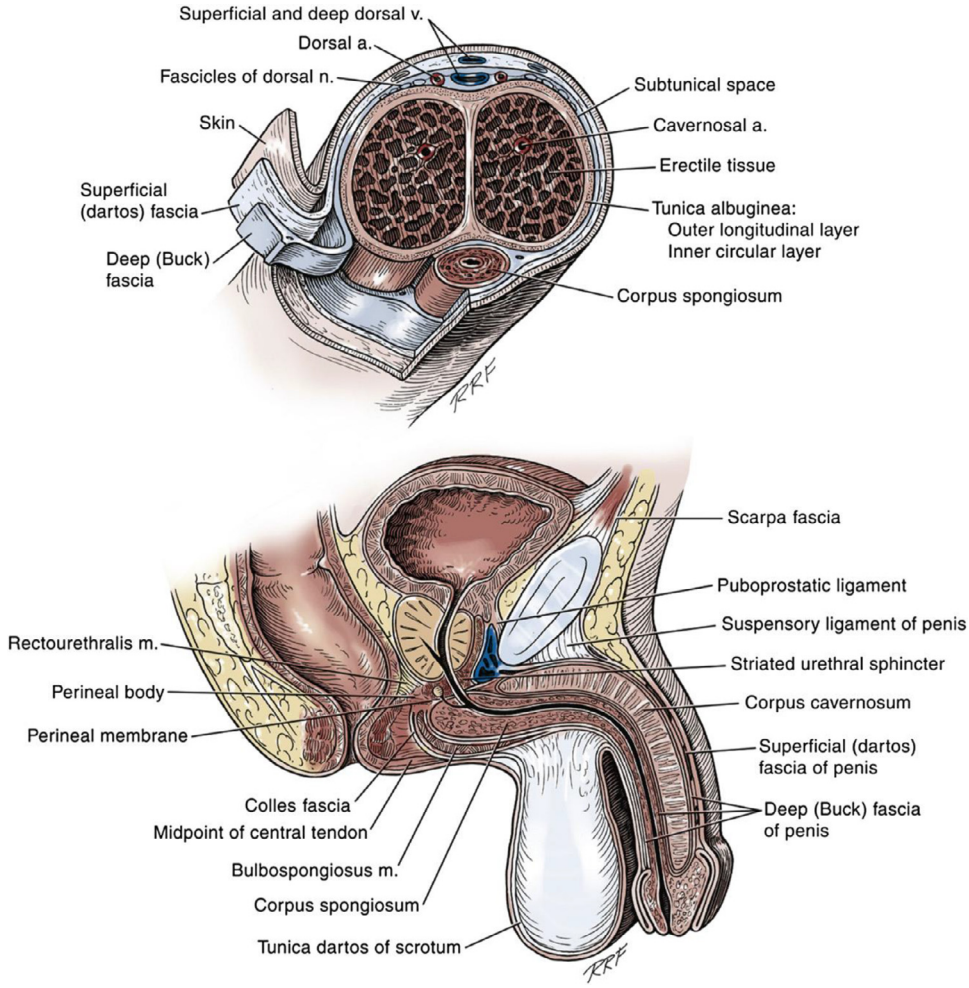

Figure 1. Penile anatomy. Figure is available in color online at www.smr.jsexmed.org.

relationship or partner factors, and treatment goals.[9] Clinicians might also consider the implementation of a questionnaire to supplement the interview. Validated questionnaires have proven to help quantify the patient's assessment of his erection. Notable questionnaires include the Male Sexual Health Questionnaire[13] (MSHQ), Erectile Dysfunction Inventory for Treatment and Satisfaction[14] (EDITS), International Index of Erectile Function[15] (IIEF) and the Erectile Hardness Score[16,17] (EHS). While many questionnaires exist, those of greatest clinical utility demonstrate consistency, reproducibility, sensitivity, specificity, and validation across languages and different cultural contexts. For the purposes of this paper, the focus will be on the International Index of Erectile Function[15] (IIEF) and the Erectile Hardness Score[16,17] (EHS).

The IIEF is a patient-reported outcome measure (PROM) that addresses multiple domains of male sexual function, including erectile function, orgasm, libido or desire, sexual satisfaction, and overall satisfaction.[9] The inventory is available as a complete, 15-question form (IIEF-15) or a short form with only 5 questions (IIEF-5), which specifically focuses on erectile function and satisfaction. The IIEF-15 has been validated across many different ethnic and geographic contexts.[18] The complete form has also demonstrated strong internal consistency, test-retest reproducibility, sensitivity, and specificity across multiple studies.[9] The IIEF-5 short form of this inventory has demonstrated good validity and may be preferred for focused return visits; however, it cannot be used to differentiate between organic, vasculogenic, and psychogenic causes of ED.

The IIEF represents a way of quantifying erectile function and other aspects of sexual function as a patient-reported outcome. Before the widespread acceptance of IIEF, a simple, single-item instrument was established to quantify erection rigidity, the Erectile Hardness Score (EHS).[17] This tool asks patients to assess the degree of tumescence of their erection on a scale of 0 to 4. Here a score of 0 indicates a penis that "does not enlarge" vs a score of 4 signifies a "penis that is completely hard and fully rigid".[17] Goldstein et al[17] found that the score on this instrument directly correlated with the likelihood of successful sexual intercourse; thus, they posed that the tool could serve as a proxy for providers to understand the sexual function of patients. Key benefits of the

EHS are its simplicity and its ability to clinically assess medical or surgical interventions.

Questionnaires are an integral component of the patient history; however, they are not a surrogate for physical examination. These instruments allow for the subjective grading of erectile function from a patient's viewpoint, but this does not provide objective data. Thus, the remainder of this paper will explore objective techniques to assess penile rigidity.

Intracavernosal Injection Therapy Testing

Prior to the invention and adoption of oral phosphodiesterase inhibitors, injection of vasoactive agents into the corpora was the mainstay of non-surgical treatment for erectile dysfunction.[19] Intracavernosal injection (ICI) therapy is widely used in the management of erectile dysfunction and for diagnostic purposes. Initially, vasoactive medications such as papaverine and phenoxybenzamine were employed as single agents, however adverse events such as priapism and cavernosal fibrosis[20] are known risks. Papaverine is a non-specific phosphodiesterase (PDE) inhibitor that causes smooth muscle relaxation via accumulation of cAMP, which results in increased penile arterial inflow with simultaneous venous outflow resistance.[21] Alpha-adrenergic receptor antagonists, including phenoxybenzamine and phentolamine, are another class of medications that promote erection[22] via corporeal smooth muscle relaxation by increasing blood flow and inhibiting anti-erectile α_1 receptors.

Presently, the primary and only FDA-approved medication employed for ICI is a synthetic prostaglandin E1, alprostadil, which induces tissue relaxation by activating adenylate cyclase (AC), thereby increasing the production of cAMP. Adverse events related to this medication include injection-site pain as well as prolonged erection and penile fibrosis.[23] Often, alprostadil is incorporated into mixtures with other synergistic medications and used as combination therapy, such as with Bimix (alprostadil + phentolamine) and Trimix (alprostadil + phentolamine + papaverine). Combination therapy allows for the use of the individual medications at lower dosage in hopes of evading specific primary adverse outcomes associated with monotherapy, while maximizing efficacy of erectile rigidity.[24] Additional adverse events associated with ICI include penile hematoma, and rarely, infection or cavernous thrombosis.[25] Despite these potential risks, ICI continues to be utilized as a second-line treatment of erectile dysfunction. Importantly, ICI may be employed prior to the administration of the EHS questionnaire to provide an objective measure of the efficacy when a patient is considering ICI as a primary treatment for ED.

ICI is mentioned here not only for therapeutic purposes but also because it has become an instrumental tool in diagnosing and evaluating ED. ICI has also been incorporated into multiple diagnostic strategies as a means by which patients may achieve an erection in the clinical setting where one may not otherwise become easily aroused. ICI is the most reliable technique when evaluating the magnitude of penile curvature in patients with Peyronie's disease. ICI is frequently combined with penile doppler ultrasound to detect aberrations in vascular status and examine for vasculogenic causes of ED.[26]

Duplex Ultrasound

ICI in conjunction with penile duplex ultrasonography (PDU) represents the currently preferred[7] evaluation of penile vasculature and vasculogenic causes of ED.[26] PDU is used to evaluate blood flow during different intervals of the penile erection, typically at the penoscrotal junction. The evaluation begins with injection on an erectogenic medication, then some form of stimulation (eg, self-manual, audiovisual, or even repeat injection), followed by an assessment of blood flow via PDU. The technologist should use a high-resolution ultrasound probe positioned at the base of the penis,[27] taking care to evaluate both arteries. Measurement at the penile base (eg, the penoscrotal junction) allows for more accurate and reproducible measurements.

The primary variables that are assessed include systolic velocity (PSV), arterial diameter, end-diastolic velocity (EDV), resistive index ([PSV − EDV] / PSV), and degree of cavernosal dilation after induction with an erectogenic agent. As the erection occurs and the intracavernosal pressure increases, the blood flow initially rises, then the diastolic flow decreases and reverses direction until the arterial waveform is dampened such that no diastolic flow is detected.[28] It must be noted that caution should be used when examining the values produced by the study, as they are not meant to be interpreted in isolation. For instance, variance in technologists may result in increased probe compression, which may reduce arterial inflow and thus decrease PSV. Additionally, while an elevated EDV is usually indicates a venous leak, it loses specificity if associated with simultaneous arterial insufficiency.[29]

The physiology of penile erection requires patent vascularity to allow for sufficient arterial inflow while ensuring adequate collapse of the venous outflow to maintain rigidity. As such, in a patient with a complaint of ED, Hattery et al established that PSV > 25−35 cm/s[30] and EDV < 3−5 cm/s are most consistent with non-vasculogenic etiologies,[31] meaning the cause is not due to diminished arterial flow nor venous leak. Resistance index (RI) less than 0.75 is generally associated with veno-occlusive disease, whereas a value of 1 or greater is considered normal.[28]

Results from ICI and PDU are subject to additional variables including patient anxiety, discomfort, and unfamiliar surroundings. Similar to urodynamic studies, the penis can sometimes be an "unreliable witness" in the office setting.

The use of ICI and PDU is strictly for the establishment of whether a patient has vasculogenic ED. Therefore, the test is not meant to make assumptions regarding neurologic or hormonal influences on the penile erection. Additional limitations

to the use of PDU include the necessity of accurate dosing of vasoactive agents and discrete duration for which these agents exhibit their effect.[27] When using injectable agents, testing should occur within 1 to 20 minutes following administration; failure to do so may result in gradual reversal of erection and inaccurate results. In the case of drug reversal, this may require re-dosing, which may not only been uncomfortable and inconvenient for the patient but also compounds the previously mentioned risks of ICI.

Similarly, penile angiography may be employed for the diagnosis of vascular ED. This invasive test is for patients that tested positive on PDU and may be candidates for revascularization procedures, such as those with posttraumatic ED.[32] Interestingly, some patients may experience a psychological benefit following identification of an anatomical abnormality with angiography.[33] Penile arteriography is focused on patency of vessels and does not give insight regarding penile hardiness or rigidity.

Nocturnal Penile Tumescence Testing

Centuries ago, erectile dysfunction was categorized as a *natural* or *supernatural* disorder, referring to idiopathic impotence or that which was due to evil spells.[2] ED was later subcategorized into "organic" or "psychogenic" pathology.[34] Here, psychogenic ED referred to that which was caused by anxiety, guilt, depression, or mental conflict, whereas organic ED referred to a pathology that was secondary to other medical processes, such as cardiovascular or neural disease. However, these definitions continue to oversimplify the hormonal, neural, psychological, and vascular systems which constitute a male erection. For instance, it is estimated that 45% of patients with ED have psychogenic ailments,[35] which may be contributory.

Nocturnal penile tumescence testing (NPT) originated because of observations of physiologic changes with different stages of sleep and a rudimentary understanding of the psychological aspect of the erection. Fisher[36] noted that spontaneous erections occur during the rapid eye movement (REM) phase of sleep. In detail, during REM, there is at least one erectile event with >60% tip rigidity that lasts an average of 10−15 minutes. Historically, evidence of this would indicate that the patient had sufficient neuro-vascular-endocrine function to result in an erection, and physicians would deduce that the patient suffered from psychogenic ED. Normal penile nocturnal erections meant that patients had well-functioning vascularity, neuronal functioning, and an anatomically sound phallus capable of facilitating sexual penetration.

There are many ways by which NPT may be performed, such as with sleep laboratory testing, the erectometer, and others. Historically, students have been taught the stamp test,[37] whereby a patient places a roll of stamps snuggly around his penis prior to bed, and if they are torn upon waking, he does not have organic ED. Present-day studies have used more precise means of nocturnal penile tumescence testing to discover additional biological information about patients with ED. For instance, Yilmaz[38] uncovered decreases in the quantity of intracorporeal smooth muscle cells in patients with ED vs those without, which correlated with NPT response. Thus, while NPT cannot directly grant information about penile hardness, it may be a useful tool to do so when combined with other modalities.

Currently, NPT often employs the RigiScan device (Dacomed Corporation, Minneapolis, MN, USA). This device was initially introduced by Bradley[39] et al to measure penile circumference and radial rigidity in real-time continuously. This non-invasive, ambulatory tool has been shown to be effective in differentiating psychogenic ED from ED due to other causes with sensitivity and specificity greater than 80%.[40] The device consists of 2 expandable loops placed on the distal and proximal ends of the penis, and a monitor which is strapped onto the patient's leg via a holster (Figure 2). The device measures percentage increases in penile radius, which translates to differences in radial rigidity. Radial rigidity is dependent on intracavernosal pressure and varies with surface wall tension forces.[41] Tip and base rigidity greater than 60% have been accepted as adequate rigidity for vaginal penetration[40] based on studies that demonstrate a good correlation between radial radiation and axial buckling forces.[41,42] However, this correlation has been debated as studies have demonstrated conflicting results.[42,43]

Assessment of Axial Rigidity With Digital Inflection Rigidometer

Axial rigidity, which is a function of erectile tissue mechanical properties and penile geometry, refers to the ability of the erect penis to withstand axial loads such as compressive vaginal forces during intromission and pelvic thrusting following penetration.[41] Beyond radial tissue expansion, as is measured by RigiScan, sufficient axial rigidity is necessary for a successful penetrative sexual encounter. It is also worth noting that the clinical utility of the RigiScan is uncertain as it is not well understood how representative nocturnal, reflexive erections are to spontaneous sexual or erotic erections.

In addition to the RigiScan, many of the available instruments to measure rigidity are similarly based on the examination of radial rigidity.[41] Conversely, the Digital Inflection Rigidometer (DIR) was introduced by Barbarà[44] in the late 1990s as a tool by which we may examine axial rigidity directly. This instrument, designed to measure longitudinal penile force, consists of a cylinder that encases the penis connected to the monitor. A sensor resides at the distal end of the cylinder, which the erect penis is pressed against until penile buckling occurs. Here, axial rigidity relies on penile geometry and essential tissue mechanical properties, including cavernosal compliance and tunical distensibility.[45] The former refers to the ability of the corpus cavernosa to engorge with increased volumes while maintaining low pressures, and the latter involves the flexibility of the surrounding tunica

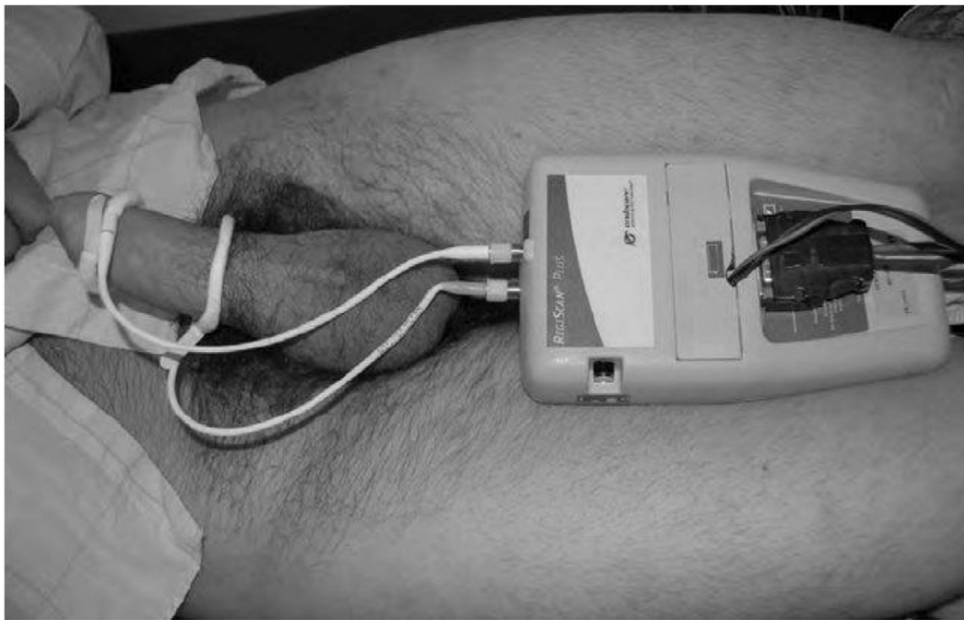

Figure 2. RigiScan.

albuginea. It has been established that rigidity greater than 500 grams[46] is congruent with satisfactory penetrable sexual intercourse without a bend in the penis. The degree of axial rigidity as measured by DIR has been shown to correlate with subjective, patient-validated questionnaires such as the IIEF.[47] Similarly, axial rigidity measurements have been examined in patients following implantation of penile prosthesis, and these results corresponded with patient and partner satisfaction.[48] Thus, measurement of axial rigidity, rather than radial rigidity, may be a more appropriate proxy for an actual penetrative sexual encounter.

DIR has many clinical benefits, which deem it a useful test for direct assessment of erectile hardness. It is an easy-to-use instrument for both the patient and the clinician or technician administering the instrument. Conducting this test is not time-consuming and does not require overnight or prolonged participation by the patient. Additionally, this test is painless for the patient. However, this instrument has many limitations, including its inability to measure penile rigidity continuously. This instrument is only able to give static information at a given time during the erection. Its lack of portability is also a limitation; the instrument may only be used in the clinical setting rather than at home to measure realistic, erotic erection.

Shear Wave Elastography

Another way by which tissue stiffness may be quantified with ultrasound is shear wave elastography (SWE). SWE is a non-invasive tool that sends an acoustic impulse through tissue to generate molecular vibrations, which create shear waves in the tissue (Figure 3). This is in contrast to classic strain elastography, which requires manual compression to calculate tissue displacement.[49] Here the speed of the waves is proportional to the tissue elastic value. Thus, the magnitude of tissue stiffness can be measured directly from detection of shear wave velocity (SWV). In a study by Inci et al,[49] the authors proposed that penile rigidity, as measured by density of smooth muscle cells in the corpora cavernosum, may be quantified with use of SWE. Smooth muscle cells were considered the primary determinant of corporal rigidity, as these cells represent the main functional density of the penis and are said to decrease with age[50,51] and decreasing testosterone which results in sinusoidal occlusions and fibrosis.[52]

Inci et al[49] examined 60 healthy men of mean age 47 years, which they divided according to age (greater than or equal to vs less than 50 years). All the participants were examined while the penis was in the flaccid state by the same radiologist with measurements occurring at the glans, mid-shaft, and base of the ventral penis in transverse and longitudinal views. Of note, both corpora were measured. Ultimately, they found that average SWE measurements were significantly higher (25.2 kPa vs 18.5kPa, $P < .01$) in the older group of participants, thus demonstrating a positive correlation between age and increased corporal stiffness presumably due to decreased smooth muscle cell density. Of note, measurements at the glans were found to be significantly lower than elsewhere along the penis, which the authors inferred was due to the presence of corpus spongiosum within the glans containing fewer smooth muscle cells.

Since all the participants were examined in the flaccid state, we cannot necessarily infer the implications this may have on sexual function. Additionally, their study assumed that density of smooth muscle cells decreases across the population at age 50, which they used to create their participant groupings. This assumption was not validated with histology. SWE has also been

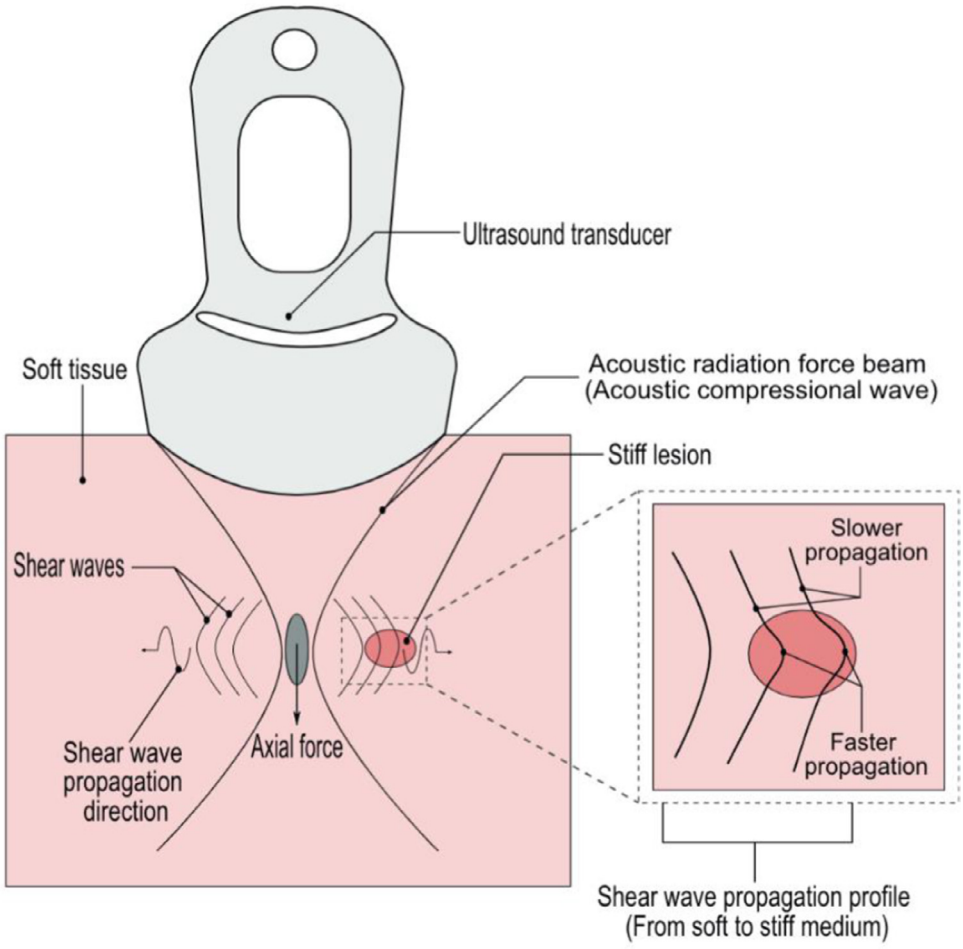

Figure 3. Shear wave elastography. Figure is available in color online at www.smr.jsexmed.org.

implemented in experimental rat models as well as recently by Camoglio et al in evaluation of children with hypospadias.[53] In the latter study, the authors used SWE in their preoperative evaluation to assist with decision on surgical technique.

Lastly, in a recent study by Aybar,[54] authors measured SWE values in men with ED secondary to arterial insufficiency, venous insufficiency, and a group of controls. They found that the control group of men without ED demonstrated a mean flaccid SWE measurement of 14.75 +/ 0.51 and rigid SWE measurement of 13.41 +/- 0.36 kPa. Further examination of SWE is needed to establish appropriate ranges that may be used in the clinical setting.

Virtual Touch

As axial and radial rigidity are synergistic components of the penile erection, one may conclude that the most optimal means by which a true marker of penile hardness may be assessed would require a tool that combines these two aspects of rigidity. Virtual touch tissue quantification (VTTQ) aims to achieve this by application of ultrasound acoustic radiation force impulse (ARFI) imaging to detect tissue rigidity by measuring shear wave velocity (SWV) values.[55,56] ARFI imaging measures tissue stiffness by short-duration acoustic radiation forces that produce localized displacements in a certain region of interest[57–59] where shear waves are generated without the need for external compression.[60] The velocity of a shear wave is proportional to tissue rigidity; assuming linear, isotropic, and elastic body.[61] Thus, stiffer tissues propagate shear waves faster than flexible ones.

In a study by Zheng et al,[55] 36 healthy male participants of mean age 34.6 years were examined while erect and VTTQ measurements obtained. Penile erection was graded following ingestion of 100 mg of sildenafil 1 hour prior to stimulation by masturbation. Patient and one of two urologists both graded the erection using a scale from 0 to 4, where 0 represents flaccidity and 4 indicates full tumescence and rigidity, allowing for penetration without difficulty. Ultrasonographic examinations were performed by 2 radiologists using a predetermined mechanical index of 1.0 and tissue harmonic imaging of 8 MHz. Using a single cavernous body, 3 SWV measurements each were taken at the glans, body, and base of the penis; these values were then averaged.

With increasing grade of erection, SWV decreased significantly ($P < .001$); thus, SWV negatively correlated with penile rigidity. Over the erection event, Zheng and colleagues noted that erectile tissue within the observed region of interest decreased as blood flow increased. Low SWV values correspond with greater fluid. Herein, VTTQ was able to measure penile rigidity accurately and objectively as a means to assess erectile function. Additionally, the study by Zheng found no differences between axial and radial rigidity when VTTQ was used to assess these parameters. However, there are several limitations to this method of quantification. Participants were instructed to induce erection by masturbation, which may be inadequate for many men. Additionally, testing was performed in a laboratory setting rather than one allowing for spontaneous or erotic events. The researchers used a subjective, semi quantitative grading scale as a comparison for SWV measurements. Results may be more profound if the measurements were compared to another objective tool.

NIRS & Photoplethysmography

Near-infrared spectroscopy (NIRS) is a non-invasive technique that allows for the continuous assessment of changes in hemoglobin concentration within an organ. This methodology has been used in the examination of testicular[62] and renal cortex oxygenation, as well as in penile hemodynamics. NIRS accurately describes the local oxygen utilization in organs that reflects the balance between oxygen delivery and oxygen consumption[63] irrespective of arterial pulse. Burnett et al[63] applied this technology in examination of the erectile function in 56 men with simultaneous implementation of color duplex ultrasound, penile circumference measurement via strain gauge monitoring (circular device that measures a sustained change in penile circumference with engorgement), subjective clinician assessment of erection by visual inspection and palpation, and measurement of axial buckling force with penile tonometry for comparison. As penile tumescence occurred and penile blood flow increased, the NIRS signal decreased, consistent with expected changes in blood volume. They found that penile blood volume changes, as measured by NIRS, correlated strongly with subjective assessment of erection quality, axial penile rigidity, and maximum penile circumference increase. Thus, this study demonstrated that NIRS correlates well with other determinants of penile erection. Moreover, beyond assessment of the cavernous arteries as measured with duplex ultrasound, NIRS addresses accessory vascular components of the penis that contribute to erection.

Photoplethysmography (PPG) is a tool that uses NIRS technology but also grants information regarding arterial volume changes[64] during erection. PPG uses the dynamics of light absorption to calculate blood volume variations in arterial blood after removing that which is due to tissue and venous hemoglobin (Figure 4). This technology is especially useful in its portability, as it is often applied in pulse oximetry to estimate arterial oxygen saturation.[65] Pong et al[64] examined PPG waveform in 68 men with varying degrees of ED and demonstrated that the amplitude differences index of the cavernous artery was positively correlated with IIEF questionnaire, clinician-determined EHS, and resistive index on Doppler. They ascertained that the PPG amplitude at the conclusion of erection may be a predictor for erectile hardness.

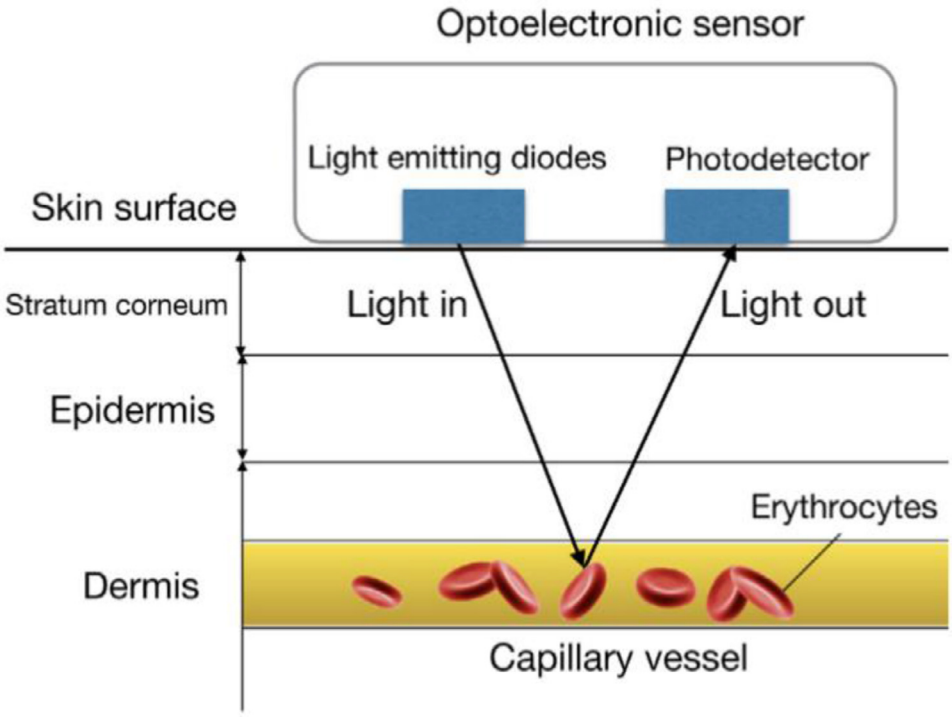

Figure 4. Photoplethysmography. Figure is available in color online at www.smr.jsexmed.org.

NIRS and PPG have many advantages including portability, ease of use, low cost, and good safety profile. However, certain limitations must also be addressed. Results may be highly variable depending on location of sensor placement,[66] introducing potentially inaccurate conclusions due to operator error. Additionally, this tool makes inferences about penile rigidity based on hemoglobin concentration or blood flow changes as a surrogate for direct measurement of tissue stiffness. In the study of a patient with erectile dysfunction, this mode of technology is only able to assess vascular patency and thus may not be helpful for those patients with non-vasculogenic causes of erectile dysfunction.

Additional Considerations

Many techniques have been developed to assess penile rigidity. Validated questionnaires such as the IIEF and EHS are easy to administer and critical to gathering important components of patient history including subjective patient-based assessments. As such, the use of validated questionnaires has been incorporated into the American Urological Association (AUA) guidelines on Erectile dysfunction and the European Association of Urology (EAU) Sexual and Reproductive Health guidelines.

This paper reviews several techniques available that can glean information regarding penile tissue rigidity. Methods such as the RigiScan, DIR, SWE, NIRS and PPG measure different physiologic properties of the phallus to yield information about tissue stiffness. Although innovative, these existing techniques are expensive, time-consuming, and use in the office setting may prove difficult for many patients and cumbersome to inexperienced staff. As such, implementation of these methods into daily, clinical practice may not yet be feasible or even unnecessary as most patients with ED are able to be managed without use of additional testing or studies. However, in patients with complex ED or in situations where management course may be altered, the AUA does recommend that 'specialized testing' be performed such as ICI testing with duplex US, NPTT, etc. In these situations, it would behoove the primary provider to consider referral to experienced colleague or center with available equipment and expertise.

Additionally, the studies mentioned above lack diversification of patient population to include variance in sexual orientation and gender identity. Homosexual men have been shown to be more likely to report symptoms of erectile dysfunction than their heterosexual counterparts.[67] The level of psychosocial complexity surrounding sexual orientation and arousal should be considered when assessing a patient's degree of penile hardness. Future study would benefit from examination of increasingly diverse subject population with respect to sexual orientation and gender identity.

RESULTS

There are several questionnaires and techniques that assist in the evaluation of penile erectile hardness. As such, this review aimed to provide a global overview of the most utilized options in order to provide practicing urologists balanced views on currently available approaches.

The use of validated questionnaires, such as IIEF and EHS, to aid in patient history gathering is essential to uncover possible psychosocial, environmental, and biological barriers that may be contributing to a patient's ED. These are simple to administer, inexpensive, and easily gather essential components of patient history. In addition, the questionnaire responses lay the groundwork for defining patient treatment goals, which will help guide patient management and treatment options. It is essential to use questionnaires in conjunction with physical examination techniques to understand a patient's disease process better.

Techniques such as RigiScan, DIR, SWE, NIRS, and PPG will reveal penile tissue rigidity by examining different physiologic properties that constitute tissue stiffness. Similarly, procedures such as ICI and duplex ultrasonography are help examine vasculogenic causes of erectile dysfunction; however, they cannot provide additional insight into alternative causes.

Many of these studies rely on vascular properties of the penile erection, and while arterial patency and robust arterial flow along with appropriate coaptation of venules are essential for penile erection, these are not the only determinants of erectile hardness. Additional factors of importance include expansibility of the corpora, intracorporeal pressure, elasticity of the surrounding tunica; all of which are measures of axial and radial force.

CONCLUSION

At present time, there is no single questionnaire or imaging technique that is perfect and all encompassing. Axial and radial rigidity are synergistic and critical components of the penile erection. Both measures provide information regarding the ability of the erect penis to successfully withstand the penetrative and compressive forces required for sexual intercourse. Virtual Touch Tissue Quantification (VTTQ) is a promising technology that provides information regarding these two aspects of penile rigidity. In the future, it may be a particularly useful tool in the accurate assessment of penile hardness. With further testing and generalization, VTTQ, along with the continued use of validated questionnaires presents an encouraging future for the objective assessment of erectile hardness.

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