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Predicting penile size during erection

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The aim of this prospective study was to identify clinical and engineering parameters of the flaccid penis for prediction of penile size during erection. Dorsal and ventral penile lengths, as well as base and tip circumferences were measured in flaccid states, gently stretched states and at full erection resulting from intracavernosal injection of prostaglandin E1 in 55 patients. The forces required to stretch the penis were measured by a specially designed gauge and regression relationships of the measured dimensions were calculated. An engineering model was developed to analyze differences between results obtained during stretching and erection, as well as to approximate the optimal force values which should be applied during the stretching part of the clinical evaluation of penile size. The ratio between the flaccid to stretched penile lengths was shown to be the best predictor for the ventral elongation from flaccid to erect penile lengths. The engineering analysis predicted that a minimal tension force of approximately 450 g during stretching of the penis is required to reach the potential erection length. The stretching forces exerted by the urologist in the clinical setting were experimentally shown to be significantly ($P < 0.01$) less than this value. The values of the relative and absolute elongations of the stretched penis at its ventral aspect provide reliable estimations of its potential maximal elongation during erection. The model designed for this study may obviate the use of intracavernosal injections for estimating penile length during erection. *International Journal of Impotence Research* (2000) **12,** 328–333.

Keywords: erectile function/dysfunction; cavernosal expandability; erectile tissue mechanical properties; biomechanical model

Introduction

Evaluation of penile size during erection is a routine clinical procedure in the diagnosis and prognosis of patients who are candidates for reconstructive surgery of the penis. Since postoperative variations in penile size may follow different types of penile surgery, eg the Nesbit procedure, Peyronie's plaque removal,[1] penile augmentation and penile prosthesis implantation, information on penile dimensions is essential in the planning process of penile operations as well as during patient counseling. Pre-surgical information of potential penile dimensions is therefore important for both the surgeon, in terms of establishing guidelines for augmentation and for the patient, in terms of realistic expectations. The simplest method to obtain this information is to measure the length of the penis during full erection with an ordinary ruler. However, an erection produced by an intracavernosal injection may bear the risks of priapism,[2] requiring immediate treatment to prevent fibrotic changes to the intracorporal erectile tissue, which could lead to erectile dysfunction (ED). For this reason, it would be advantageous to have a method for predicting penile size during erection without the use of intracavernous injections. Several methods for penile length measurement have been introduced.[3–6] Penile length and circumference in the flaccid state were measured with the intent of determining the size of the erect penis. However, these measurements were found to be inadequate for estimating penile extensibility, which corresponds to the difference between the flaccid penile length and its length following application of a constant traction until maximum stretch is achieved. The present study was designed to determine whether penile size during erection could be predicted by measurements during non-erect states and to evaluate the accord between penile stretching forces measured in the clinical setting and forces predicted by an engineering model.

Methods

Patients

Seventy patients who were evaluated for ED at the Erectile Dysfunction Clinic of the Tel-Aviv Sourasky

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Medical Center were considered for participation in this study. They underwent a detailed medical and sexual history, physical examination, psychological profile and determination of blood serum testosterone, glucose and renal profile according to the National Institute of Health (NIH) statement on ED.[7] Patients with penile abnormalities such as Peyronie's plaque, hypospadias, penile surgery (except circumcision), prostate surgery and recent significant medical problems (eg cardiovascular or cerebral diseases, uncontrolled hypertension, diabetes mellitus, malignancies or pelvic surgery) were excluded from the study. Patients in whom ED could be attributed to more than one physiological origin were also omitted from the study. Fifty-five patients whose average age was 47 ± 14 y (range 21–78) comprised the final study group.

Penile measurements and data analysis

All penile measurements and evaluations were performed by the same investigator (JC), thereby eliminating inter-observer variations. Only patients who achieved full erection (and without penile curvature) were included in the final analysis. The study was conducted in a dimly lit private room, and the patient was in supine position. Penile length was measured by a caliper. While measuring penile length at the dorsal aspect, the caliper was pushed into the pubic bone in order to eliminate the effect of the pubic fat pad. Penile length was measured dorsally from the pubo-penile angle to the meatus, and ventrally from the penoscrotal junction to the meatus side. Circumference was measured by an ordinary 'tumo-meter' at the penile base and at the corona. Penile dimensions were measured in a flaccid state and during axial stretching in which the glans was gently stretched until the patient expressed discomfort.

The stretching force applied by the urologist was measured in 24 cases, using a custom-made gauge designed to measure the force required for penile stretching until discomfort was reported (Figure 1). Length and circumferencial dimensions were measured again during full erection induced by an intracavernous injection of 10 μg prostaglandin E1. Measurements were repeated after 15 minutes after full erection had been achieved.

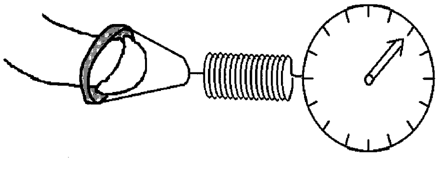

Figure 1 Schematic description of the gauge used to measure the stretching force (in g) of the penis.

The relative elongation at both the dorsal and the ventral aspects of the penis were determined by the stretch ratios for the stretched state λ_s and the erect state λ_e, using the following relationships.

$$\lambda_s = \frac{L_s}{L_f} \tag{1}$$

$$\lambda_e = \frac{L_e}{L_f} \tag{2}$$

where L_f, L_e and L_s are the lengths (in cm) of the penis in the flaccid, erect and stretched states, respectively. Linear regression equations and correlation coefficients (R^2) were calculated, and the relationships between penile dimensions in these three states were analyzed in order to determine the best predictor for penile dimensions during erection.

Engineering analysis

An engineering analysis was conducted to predict the length of the penis when a stretching force is applied compared with its length during pharmacological erection. The physiological process of erection is a complex one, as are the geometry and behavior of the biological materials. However, from a biomechanical perspective, and for first order predictions, the penis can be modeled as a blood-filled circular cylinder (Figure 2a) in which the cylinder walls represent the tunica albuginea, which is the main load bearing structure.[8]

The axial stress, σ_e, in a unit volume of the cylinder wall during erection (Figure 2a) can be determined from the relation.

$$\sigma_e = \frac{\pi P r^2}{\pi (R^2 - r^2)} \tag{3}$$

where P is the internal cavernosal pressure and r and R are the inner and outer radii of the cylinder, respectively. The mechanical characteristics of the material of the cylinder's wall (or the tunica albuginea) can be defined by the modulus of elasticity, E. It is further assumed here that the cylinder walls are made of a homogenous isotropic material with identical properties in the axial and radial directions, and thus, the elastic modulus is constant.[9,10] Accordingly, the mechanical stress-deformation relationship also yields that,

$$\sigma_e = E\frac{L_e - L_f}{L_f} = E(\lambda_e - 1). \qquad (4).$$

Using equations (3) and (4), one can determine the penis length during erection by

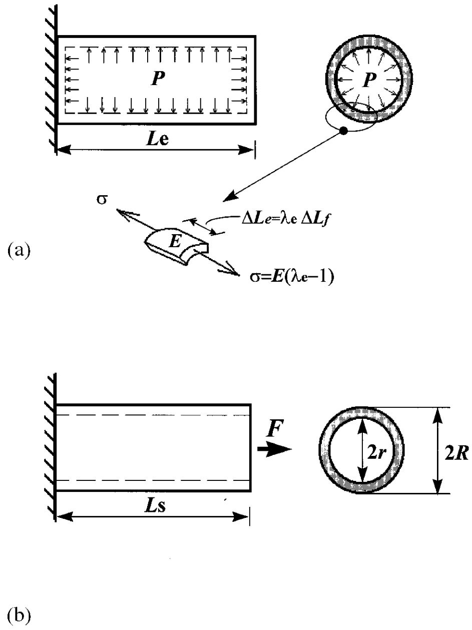

Figure 2 Simplified engineering models of the erect penis (a) a cylindrical reservoir subjected to an internal erectile pressure P, an infinitely small volume of the cylinder is isolated to delineate its stretching λ_e from flaccid state length ΔL_f to erect state length ΔL_e due to tension stresses σ, (b) a cylindrical tube, subjected to a tension force F.

$$L_e = \frac{L_f}{E(R^2 - r^2)}[Pr^2 + E(R^2 - r^2)]. \tag{5}$$

For predictions of penile length during stretching, we assume the model shown in Figure 2b. The axial stress in the cylinder wall during stretching, σ_s can be calculated from

$$\sigma_s = \frac{F}{\pi(R^2 - r^2)} \tag{6}$$

where F is the stretching force and r and R are the internal and external cylinder radii, respectively. Since the cylinder is assumed to be made of an isotropic material with linear elastic properties, the mechanical stress-deformation relationship also yields that

$$\sigma_s = E\frac{L_s - L_f}{L_f} = E(\lambda_s - 1). \tag{7}$$

Substitution of equation (7) into equation (6) yields the stretched length of the penis,

$$L_s = \frac{L_f}{\pi E(R^2 - r^2)}[F + \pi E(R^2 - r^2)]. \tag{8}$$

The ratio of L_e to L_s is then obtained from equations (5) and (8),

$$\frac{L_e}{L_s} = \frac{\pi Pr^2 + \pi E(R^2 - r^2)}{F + \pi E(R^2 - r^2)}. \tag{9}$$

Results

Penile dimensions were measured in 55 patients with ED during flaccidity, axial stretching and drug-induced erection (Table 1). Correlation and linear regression between penile lengths during erection *vs* lengths during stretching, as well as the stretch ratios of the erect penis *vs* the stretch ratios of the stretched penis are summarized in Figure 3 for the ventral aspect and in Figure 4 for the dorsal aspect. The stretching forces exerted by the urologist were measured in 24 cases. The average applied stretching force was 428 ± 3 g (range 424 − 432 g).

The length of the penis during drug-induced erection, L_e, was significantly and consistently greater than the length obtained during stretching, L_s. This phenomenon was illustrated by a plotting a dashed line (Figure 3b and Figure 4b) on which the relative elongation due to erection (λ_e) and elongation due to stretching (λ_s) are equal (unity line). Most data points obtained for both the ventral aspect (Figure 3b) and the dorsal aspect (Figure 4b) of the penis are clearly positioned above this line, indicating that the value of λ_e (or L_e) for a certain patient is almost always greater than the value of λ_s (or L_s).

The ventral stretch ratio from flaccid to stretched penile lengths was shown to be the best predictor for the ventral elongation from flaccid to erect penile lengths, with a correlation coefficient of $R^2 = 0.761$ (Figure 3b). The correlation coefficient obtained for the absolute ventral lengths (cm) of the stretched and erect penis (Figure 3a) was significantly lower ($R^2 = 0.356$) The stretch ratio relation of the dorsal penile aspect during stretched and erect states was found to produce a significantly lower correlation value ($R^2 = 0.477$), as compared with the ventral aspect measurements (Figure 4b). The correlation of the absolute dorsal penile lengths in stretched and erect states ($R^2 = 0.572$) was shown to be greater than the one obtained for the ventral aspect (Figure 4a). The stretch ratio of the ventral aspect of the penis from flaccid to erect states, λ_e^v, may thus be

Table 1 Average penile dimensions (in cm) during flaccid, erect and stretched states ($n = 55$)

	Length (average ± s.d.)		*Circumference (average ± s.d.)*	
State	*Dorsal*	*Ventral*	*Base*	*Corona*
Flaccid	8.3 ± 1.3	6.6 ± 1.3	8.1 ± 1.5	6.9 ± 1.3
Erect	13.6 ± 1.7	12.0 ± 1.6	10.9 ± 1.6	9.5 ± 1.5
Stretched	12.5 ± 1.4	10.7 ± 1.5	6.4 ± 1.1	5.3 ± 0.8

s.d. = standard deviation.

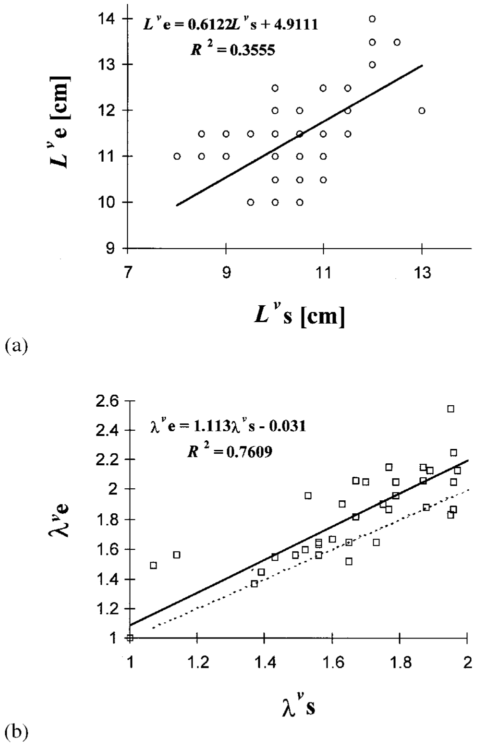

Figure 3 Correlation and linear regression between (a) ventral length during erection, L_e^v, *vs* ventral length during stretching, L_s^v, and (b) ventral stretch ratio of the erect penis, λ_s^v, *vs* ventral stretch ratio of the stretched penis, λ_s^v. The solid lines denote linear regression and the dashed line indicates unity.

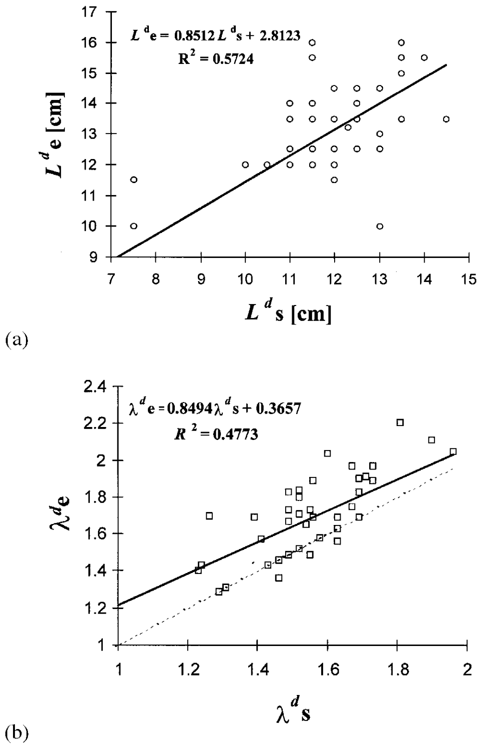

Figure 4 Correlation and linear regression between (a) dorsal length during erection, L_e^d, *vs* dorsal length during stretching, L_s^d and (b) dorsal stretch ratio of the erect penis, λ_e^d, *vs* dorsal stretch ratio of the stretched penis, λ_s^d. The solid lines denote linear

predicted using the linear regression relationship $\lambda_e^v = 1.113\ \lambda_s^v - 0.031$, where λ_s^v is the stretch ratio of the ventral aspect of the penis during stretching (Figure 3b). The elongation of the dorsal part during erection can also be predicted, although less accurately (due to the lower correlation), using the relationship $\lambda_e^d = =0.849\ \lambda_s^d + 0.366$, where λ_s^d is the stretch ratio of the dorsal aspect of the penis during stretching (Figure 4b).

The circumferencial measurements in flaccid, stretched and erect states were poorly correlated Erect *vs* flaccid penile circumference plots resulted in a correlation of $R^2 = 0.104$ for the penile base and $R^2 = 0.065$ for the corona. Plotting of stretched *vs* flaccid penile circumferences produced a correlation of $R^2 = 0.079$ for the penile base and $R^2 = 0.080$ for the corona.

The predictions provided by the theoretical analysis for the erect and stretched penis length ratio are shown in Figure 5. In Figure 5a, the length ratio is plotted against the stretching force for three different penile elastic moduli, while the cavernosal pressure is maintained constant at a physiological value of 100 mmHg.[11] In Figure 5b, the length ratio is similarly plotted against the stretching force for three different internal cavernosal pressures, while penile elasticity is maintained constant at a value of 10 MPa. This value approximates the normal elastic modulus of the main load-bearing tissue of the penis, the tunica albuginea.[12] In order to plot both diagrams, the internal and external radii of the tunica albuginea were determined as 1 cm and 12 cm, respectively, based on standard anatomic dimensions.[12] Using these diagrams, the stretching force that should be used to predict the length of the penis during erection can be estimated, assuming normal intracavernosal pressure and tunical elasticity. It was thus clearly demonstrated that in order to obtain the most accurate prediction of penile length during erection, ie to approach the value $L_e/L_s = 1$, a stretching force of around 450 g (~ 4.5 N) should be exerted.

Discussion

Penile dimensions may be altered by penile surgery,[1] and men awaiting such procedures are concerned about possible effects of the surgical

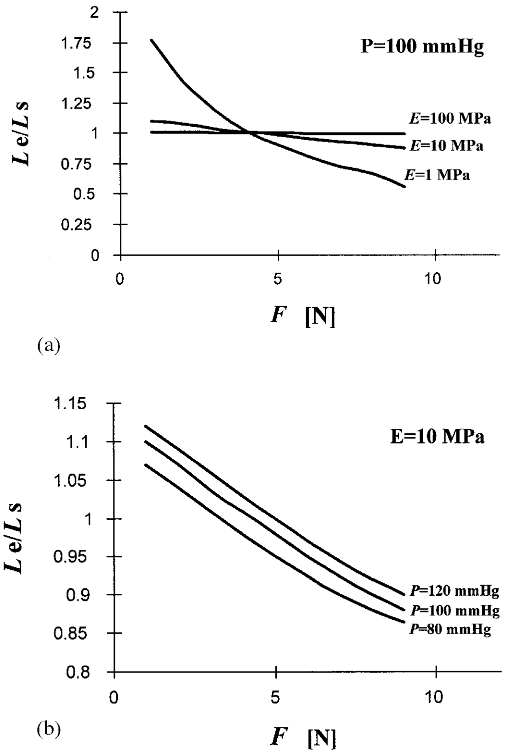

Figure 5 Predictions of the theoretical analysis, estimating the erect and stretched penis lengths ratio (L_e/L_s) *vs* the stretching force F [N] for (a) constant internal cavernosal pressure (P) of 100 mmHg, and (b) constant penile elasticity (E) of 10 MPa.

intervention on their penile size. Obtaining objective information about penile size during erection without the need for drug-induced erection has obvious advantages. This information is essential in cases when patients are candidates for correction of penile curvature or deformation, excision of Peyronie's plaque or insertion of a penile prosthesis insofar as these procedures, as well as corporal fibrosis, may alter penile dimensions. Information on penile size during erection pre- and post-intervention is highly valuable for clinical decision making and realistic expectations.

In the present study, we have demonstrated that a satisfactory correlation ($R^2 = 0.761$) exists between the elongation of the ventral aspect of the penis from flaccid to stretched lengths, and the elongation of its ventral aspect from flaccid to erect lengths (Figure 3b). Therefore, the degree of ventral penile change during erection can be predicted using a linear regression relation, as detailed earlier. The dorsal elongation of the penis from flaccid to erect lengths can also be predicted according to its elongation from flaccid to stretched lengths (Figure 4b). However, the accuracy of the latter prediction would be lower than the prediction for the ventral elongation due to the lower correlation coefficient of 0.477. The poor correlation obtained for the circumference measurements suggests that prediction of penile diameter during erection could not provide an accurate basis for stretching measurements.

Our findings can be compared with the results of Wessells *et al*,[13,14] who measured only the dorsal penile lengths in flaccid, stretched and erect states and obtained a correlation of 0.678 for erect *vs* flaccid lengths and 0.793 for erect *vs* stretched lengths. The variations between the latter results and the lower correlation coefficients obtained for the dorsal aspect of the penis in the present study may be attributed to several factors. The differences in ethnic characteristics of the patient groups used for the two studies could be one of these factors.[6] While Wessells's group of patients combined white, black and Asian subjects, our group consisted only of Caucasian Jews. In addition, our patients were younger (average age of 47 y *vs* 54 y in their study), and thus the soft tissues were more elastic, thereby contributing to increased penile extensibility.[15] Nevertheless, we succeeded in achieving adequate correlations of the stretched and erect penile lengths, especially in the ventral aspect ($R^2 = 0.761$), by using the stretch ratio parameters, λ_e and λ_s.

The theoretical approach which was used to derive equation (9) can be utilized to explain why penis length during drug-induced erections is almost always longer than the length obtained during stretching. In order to obtain a ratio of L_e to L_s that equals 1, ie equal stretched and erected lengths, the condition of $\pi P r^2 = F$ must be fulfilled. By substituting characteristic values for the arterial erectile pressure and radius of the tunica albuginea, eg $P = 100$ mmHg[11] and $r = 1$ cm,[12] we obtained a critical stretching force value of approximately 450 g. A lower magnitude of force will cause a smaller elongation of the penis, compared with its elongation due to drug-induced erection. During examination, the urologist is very cautious not to inflict pain on the patient while stretching and measuring the penis. Indeed, tension forces exerted in this study by the urologist in the clinical setting were shown to be significantly ($P < 0.01$) lower than 450 g. Hence, in this case, the penis is not stretched to its potential maximal length, as it is during physiological erection. These findings indicate the need for standardization of the force level exerted during clinical examination using a gauge which is specifically designed to apply a constant traction on the penis and thus, allows for more accurate predictions of its size during erection.

In conclusion, the ventral elongation of the penis from a flaccid to an erect state can be efficiently predicted by measuring penile elongation during stretching. Use of the novel methodology described herein may thus obviate the need for drug-induced erections for the measurement of erect penile dimensions.

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