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Characterization of Penile Erectile States Using External Computer-Based Monitoring

The states of penile erection have not been quantified to establish their relationship to intracorporal fluid pressure and to soft tissue constraint. Computer-based circumferential rigidity sensing during erectile cycles now permits circumferential size and rigidity characterization. Measurements during dynamic infusion cavernometry and cavernosography relate intracorporal pressure and axial rigidity to circumference and circumferential rigidity characterization. Tumescence/rigidity coupling and tissue elastic contributions are identified from the combined data.

Introduction

There are an estimated ten to twenty million American men with erectile impotence [1]. For those who desire therapeutic intervention, standard evaluation includes an assessment of the quality of the penile erection associated with either visual, sexual or pharmacologic stimulation during sleep [2, 3]. In general, individuals who demonstrate an excellent erection under any circumstance are suspected of having psychologic impotence, while those who have consistently poor erections are suspected of having organic impotence [4, 5].

Methodology to record the quality of penile erection has included determination of penile blood pressure, blood flow, temperature, circumference, and rigidity. The latter characteristic, penile rigidity, has proven to be the most elusive yet most informative parameter of erectile quality. Penile rigidity is the mechanical stiffness the penis exhibits to external load, and is manifested both circumferentially and axially.

There have been few studies evaluating the physical parameters of penile rigidity [5]. As normal males experience several erections during a normal night of sleep, ranging from several minutes to one-half hour in duration each, indirect sensing means to monitor the existence and quality of erections is very valuable. The assumption that penile size change, or tumescence, denotes erectile rigidity and hence axial load resistance was the basis for early strain gauge instrumentation which monitored circumferential girth [3]. Subsequent clinical experience suggested that rigidity was not adequately indicated by size changes [6–8]. New instrumentation is now available to monitor circumferential rigidity [7].

This paper presents data obtained during standard dynamic infusion cavernometry and cavernosography procedures on individuals who complained of erectile impairment. Circumferential and axial rigidities were compared for their correlation and their relation to intracorporal pressure. Circumferential loop compression of the penis with the instrumentation permitted the development of intracorporal pressure-volume relationships which display the passive capacitance properties of the penis as a pressure vessel.

Biomechanical Considerations

Unlike skeletal load carrying ability, penile rigidity is asserted through soft tissue which is placed in a three dimensional prestress state sufficient to sustain subsequent external load. Penile erection results when the cavernous blood vessels mediating increase in blood volume to the corporal bodies become constrained within their specialized lining, the tunica albuginea. Rigidity develops when expansion is sufficient to induce stress in the penile envelope and occurs only after tumescence or the change in corporal body dimension is realized (Fig. 1).

The three dimensional stress state in the tunica behaves

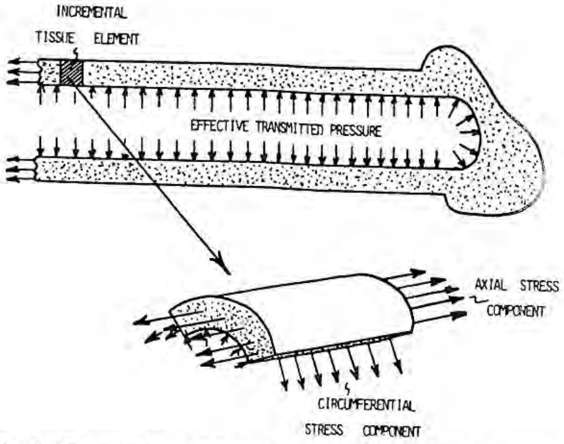

Fig. 1 Tissue stress state induced by intracorporal pressure

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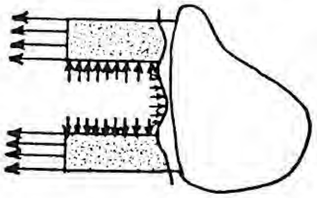
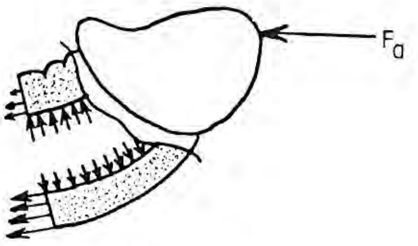
under tissue constitutive laws that are shown here to be nonlinear. The effect of sufficient volume change of the corpora induced by systemic blood pressure, which places the tissue in its nonlinear stress state, is a display of resistance to external load by the penis. For systemic pressures, this represents an initial axial resistive force per unit effective corporal area of 1.33×10^4 Pa (1.93 lb/in.^{2}). As the pe periences axial load from its initial distended state it ac closed nonlinear fluid capacitor, with an attendant axia sustained by the progressive nonlinear response of the ding tunica albuginea. For intracorporal pressure leve are inadequate or marginal, external load limits are rel buckling deformation. Buckling occurs when an axia plied external load negates the tensile stress field in propriately large region of the tunica albuginea, allowin deformation compression or bending (Fig. 2).



ERECT PENIS: INTERNAL EQUILIBRIUM



BUCKLING MODE STRESS RELAXATION

Fig. 2 Tissue prestress relaxation, buckling due to axial load

There have been few studies evaluating the p parameters of penile rigidity. The mere presence of bl the corpora, enlarging the penis to a tumesced state, is i cient to produce rigidity. Strain gauge instrumentation measures geometric size change alone cannot quantify ri because of nonlinear tissue constitutive laws [7]. Howev ternal circumferential compression of the penile sha probe-like manner from any given initial distension sta effective way to sense rigidity, if compliance of the section is recorded under calibrated compression load constraints are effective for this purpose.

Methods

Determination of axial and radial rigidity in human erection was performed during dynamic infusion nometry and cavernosography in seven patients with impotence at Boston University Hospital. In all cases, vasive erectile function study was indicated to obtain inf tion concerning possible surgical reconstruction of the o

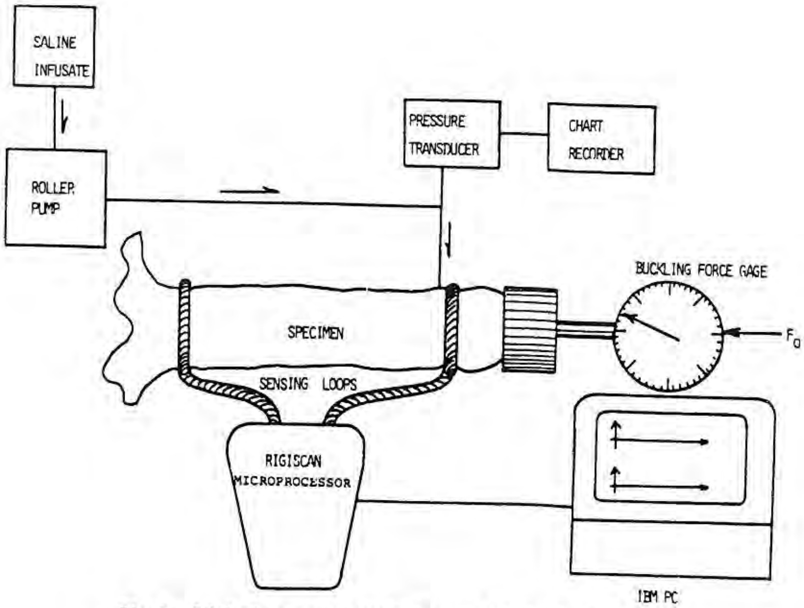


Fig. 3 Clinical instrumentation system for rigidity monitoring

Nomenclature

A_c = effective cross-sectional area of combined corpora cavernosa

A_{ta} = effective tissue area of tunica albuginea cross-section

C = fluid capacitance, cm^3/Pa

D = effective initial diameter of combined corporal pressure chamber

D_0 = diameter of penis prior to corporal filling

E = Young's modulus

F_a = axial buckling force: axial rigidity

R, % = circumferential rigidity

V = volume change of effective corporal chamber

p = gauge pressure, Pa in corpora

p_0 = gauge pressure, Pa o ing loop penile surfac compression

t = effective thickness, tu albuginea

μ = Poisson's ratio

V = pressure vessel volum

Fig. 4 Axial force measurement with assembled instrumentation and [illegible] system

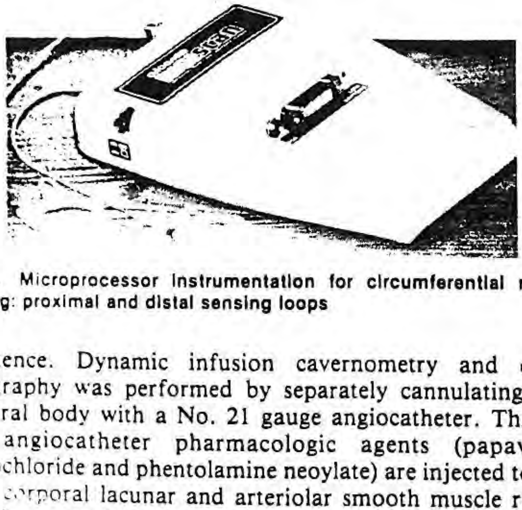


Fig. 5 Microprocessor instrumentation for circumferential rigidity sensing: proximal and distal sensing loops

impotence. Dynamic infusion cavernometry and cavernosography was performed by separately cannulating each corporal body with a No. 21 gauge angiocatheter. Through one angiocatheter pharmacologic agents (papaverine hydrochloride and phentolamine neoylate) are injected to promote corporal lacunar and arteriolar smooth muscle relaxation. The second angiocatheter was connected by sterile tubing to a pressure transducer to record corporal body pressure. After fifteen minutes following the intracavernosal pharmacologic injection, heparinized saline was infused through the same angiocatheter to augment the penile erection and raise corporal body pressure. At various levels of constant corporal body pressure the following measurements were performed: axial rigidity, radial rigidity, penile circumference, and pubis mid-glans length (Fig. 3).

Axial rigidity of the erect penis was recorded in the standard [illegible] fashion by applying an external compressive force for [illegible] second interval on the erect penis at the glans [illegible] observing for buckling deformation along the penile shaft. The axial force which caused large deformation (buckling) was defined as the axial rigidity (Fig. 4).

Axial rigidity recordings were performed at a constant corporal body pressure. If a patient with organic impotence exhibited excellent venous closure mechanisms in response to the pharmacologic smooth muscle relaxation, the corporal body pressure was sustained by occasional pulsed infusion of heparinized saline. If a patient had poor vensus closure mechanisms, the corporal body pressure was sustained by steady infusion of appropriate flow rates of heparinized saline ranging from 10–70 ml/min. During the 5–10 second time span of the axial compression any increased venous drainage from the corporal body by the increased axial load was felt to be insignificant. The corporal bodies acted as a fluid capacitor under these conditions. Axial loading forces over the 5–10 second interval caused sudden corporal body pressure spikes ranging from 2666 Pa (20 mm Hg) to greater than 33,325 Pa (250 mm Hg). The greater the corporal body pressure at the time of axial loading, the greater the height of the corporal body pressure spike.

Radial rigidity of the erect penis was recorded by new instrumentation for continuously measuring rigidity and tumescence (Fig. 5).[1] This instrumentation has been used clinically to monitor penile rigidity and tumescence during sleep. It consists of two specialized loops placed around the proximal and distal penile shaft which determine circumferential girth. When a girth change of one centimeter is monitored, a controlled 2.78N (10 oz) tensile load force is imposed on the loops and released every 30 seconds. The distortion of the penile cross-section from its unloaded state is interpreted as circumferential rigidity. Values are expressed as a percentage of distortion circumference compared to the circumference of an incompressible rod. Computer control of the loop sensing is provided by a microprocessor in the Rigiscan. Subsequent data downloading through an IBM PC permits printout to display circumferential girth and rigidity on a time base (Fig. 6).

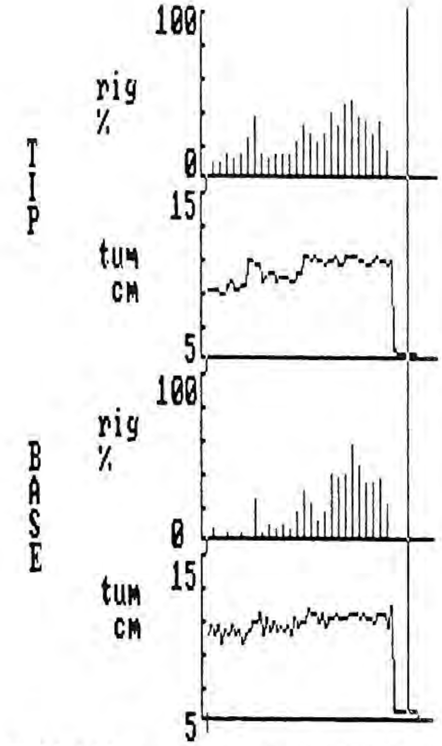


Fig. 6 IBM PC rigidity printout for clinical diagnosis of impotence

Results

Intracorporal pressures less than 70 mm Hg related in all patients to low axial rigidity; small subsequent increases in that pressure induced large increases in axial rigidity. Under exter-

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[1] Rigiscan Ambulatory Rigidity and Tumescence Monitor^{R}, Dacomed Corp., Minneapolis, MN.

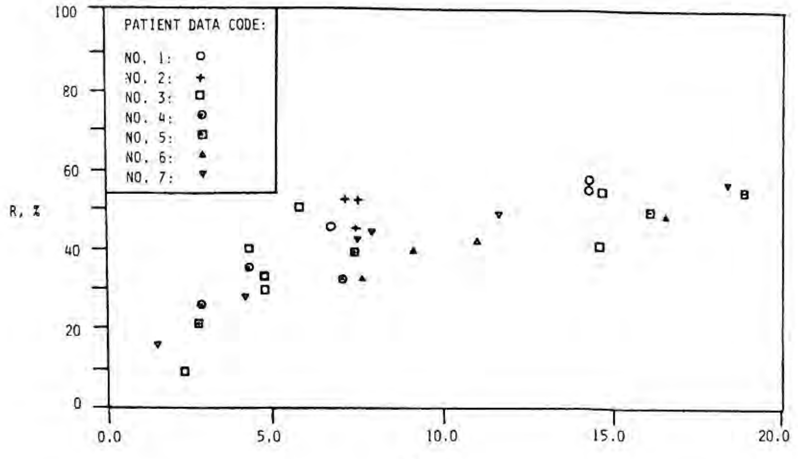

Fig. 7 Circumferential, axial rigidity data: seven patients during cavernosography procedure

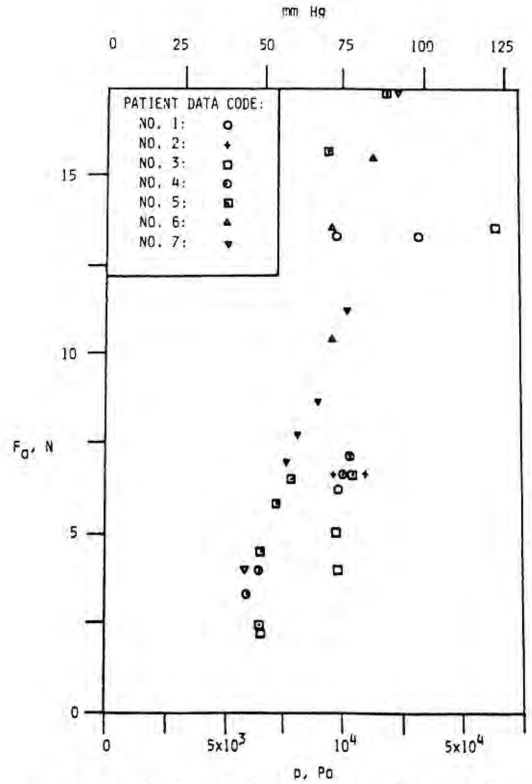

Fig. 8 Axial force, intracorporal pressure data

ternal axial load, circumferential tissue distension associated with constant penile volume during axial compression elevates corporal pressures to levels of 33,325 Pa (250 mm Hg) or greater during load application. An initial rigidity or tissue stress state was required for this pressure elevation to be induced. Figure 7 displays the relationship between circumferential and axial rigidities measured behind the glans penis. Circumferential rigidities are those immediately preceding force application. The rigidity function is nonlinear for axial buckling forces nominally below 7 N (1.6 lb). As circumferential rigidity becomes large, axial compression does not permit buckling collapse. A distinct correlation between these rigidities was also reported recently during sleep laboratory testing [5].

Figure 8 displays the relationship between axial rigidity and intracorporal pressure. Although modest rigidity was evident in two patients for pressures as low as 6650 Pa (50 mm Hg), no reliable readings were available until pressures elevated to near 9310 Pa (70 mm Hg). Data also indicated that the critical corporal body pressure resulting in increased axial rigidity preceded that of increased radial rigidity by approximately 1333–2666 Pa (10–20 mm Hg).

The capacitance characteristics of the tunica albuginea may be interpreted from the data recording circumferential and axial rigidities. Circumferential rigidity is directly related to the circumferential change recorded after application of a loop load. Axial rigidity is directly related to the stress state prior to application of an external axial load to the ends of the corporal bodies. Both are tissue stress-related. If the penis were analogous to a Laplace membrane pressure vessel, the circumferential rigidity would be functionally related to membrane parameters and pressure loading. Referencing circumferential rigidity to loop shortening from the distended circumference prior to loading:

$$R, \%/100 = [1 + (D_0/2t)(p/E)(1 - p_0/p)] / [1 + (D_0/2t)(p/E)] \qquad (1)$$

Sensing quality is derived from appropriate selection of the pressure ratio p_0/p; inappropriately small values provide rigidities insensitive to internal penile pressure (R, % = 100), whereas excessive values of the ratio compress the penis below its unpressurized size and obscure the role of pressure in load resistance. The selection of a sensing loop force of 2.78 N (10 ounces) in the Rigiscan provides effective rigidity monitoring by discerning trends in rigidity with intracorporal pressure.

Laplace vessel rigidity (equation (1)) approaches 100 percent as p/E increases for fixed values of the parameters $(D_0/2t)$ and p_0. Axial buckling load F_a is directly proportional to axial tissue distension stress through the product pA_c/A_{ta}. Therefore, equation (1) correlates circumferential rigidity with axial buckling force for a Laplace vessel. There, values of R,% approach 100 percent asymptotically as F_a increases for constant $D_0/2t$, p_0, and E. Whereas the structure and physiology of the penis are more complex, this trend is clearly evidenced in Fig. 7 in data gained on the seven patient population.

The capacitance per unit cross-sectional area of a uniform homogeneous vessel is:

$$C/L = V/p = \pi/2D^2/E[(1/2 - \mu)A_c/A_{ta} + 1/2(1 - \mu/2)(D/t)] \qquad (2)$$

Figure 9 on the patient population displays dramatic

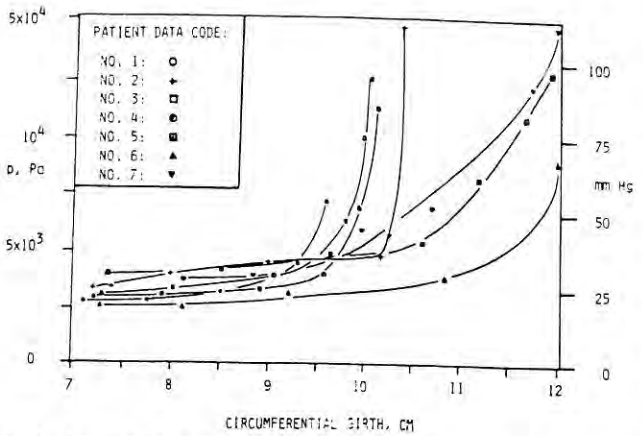

Fig. 9 Intracorporal pressure during the corporal filling mode: seven patients

nonlinearity of capacitance per unit area from intracorporal pressure—circumference data. Pressures associated with erection illustrate substantial tissue constraint there, whereas the intermediate tumesced zone permits filling with modest pressure rise.

The nonlinear character of tissue constraint may contribute to the uncoupling of tumescence and rigidity clinically witnessed at stages of erection. There, momentary reductions in circumferential rigidity occur with no change in girth. During dynamic infusion cavernometry and cavernosography, when girth was maximum, intracorporal pressure experienced momentary reductions simultaneous with rigidity. The stiffening nonlinearity at maximum girth would explain this, as fluctuations in corporal pressure in that region have great influence on axial rigidity with minimal girth change.

Discussion

Penile rigidity is the most important determination of the quality of penile erection. As instrumentation recording the parameter of penile rigidity improves, its relationship to axial and circumferential components, corporal body pressure and capacitance of the tunica albuginea may be probed.

This study demonstrates that rigidity is a function of corporal body pressure and is not functionally related to penile circumference changes. Circumferential rigidity and axial rigidity associate with corporal body pressure through a distinct functional relationship.

The capacitance characteristics of the tunica albuginea are such that at low circumferential girths filling may occur with only modest pressure elevation. At high circumferential girths, the low capacitance permits fluid constraint, elevated corporal body pressures and penile rigidity. The minor increase in capacitance in mid-range circumferential girths is unexplained. There is apparently a minimally greater compliance in the presence of some fluid engorgement of the corpora than when the corpora is in the baseline flaccid state.

The specific nonlinear characteristics of the compliance of the tunica albuginea may account for the uncoupling of tumescence and ridigity as previously observed [5]. High corporal body pressures were always associated with high rigidity values. As corporal pressure falls, rigidity values also fall, although tumescence or circumferential girth remain essentially unaltered. The uncoupling of tumescence and rigidity is functionally important and was unable to be recorded with previous geometric-based instrumentation. This finding is potenially of great significance and will be the subject of further investigation.

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