Scienta Press Journals

American Surgeon
Journal of Surgical Science and Medical Advances

Multivariate Separation of Pre- and Postoperative Urodynamic States and its Decomposition into Component Channels

Xolmurodov Mamathon[1],Akram Abdukhamidov[2], Ganiev Mukhammadbobir [3],
[1] Namangan State University, Faculty of Physics and Mathematics, Namangan, Uzbekistan
[2] Department of Pediatric Surgery, Republican Scientific Center of Emergency Medical Care Tashkent Regional Branch, Tashkent , Uzbekistan
[3]Department of Pediatric Surgery, Republican Scientific Center of Emergency Medical Care Tashkent Regional Branch, Tashkent , Uzbekistan
ORCID: 0009-0005-5057-1201
Corresponding author:e-mail: akram.abdukhamidov.md@gmail.com; muhammadboburganiyev1@gmail.com

Abstract

A surgical technique for relieving bladder outlet obstruction is normally judged by comparing eight or more urodynamic variables one at a time. This produces a list of significance statements from which no overall ordering follows, and it discards the information contained in the joint displacement of the whole profile. A single scalar measure of how far an operation moves the patient in the multivariate space of urodynamic measurements, together with a decomposition showing which variables carry that movement, addresses both shortcomings.

Keywords: multivariate space of urodynamic

Introduction

A surgical technique for relieving bladder outlet obstruction is normally judged by comparing eight or more urodynamic variables one at a time. This produces a list of significance statements from which no overall ordering follows, and it discards the information contained in the joint displacement of the whole profile. A single scalar measure of how far an operation moves the patient in the multivariate space of urodynamic measurements, together with a decomposition showing which variables carry that movement, addresses both shortcomings.

Method

Let μ_{pre} and μ_{post} denote the mean vectors of p urodynamic variables before and after operation, and Σ their common covariance matrix. The natural scale-free measure of separation is the Mahalanobis distance

$$D^2 = \left(\mu_{post} - \mu_{pre}\right)^T \Sigma^{-1} \left(\mu_{post} - \mu_{pre}\right). \quad (1)$$

When only marginal summary statistics are published, Σ is unavailable and (1) is evaluated under the diagonal approximation $\Sigma \approx \mathrm{diag}(s_1^2, \ldots, s_p^2)$, with each variable pooled across the two states,

$$s_i = \sqrt{\frac{s^2{}_{pre,i} + s^2{}_{post,i}}{2}}, \quad d_i = \frac{\mu_{post,i} - \mu_{pre,i}}{s_i}, \quad (2)$$

$$D = \sqrt{\sum_{i=1}^{p} d^2{}_i}\,. \quad (3)$$

Each variable's share of the squared separation follows immediately,

$$w_i = \frac{d^2{}_i}{D^2} \cdot 100\,\%, \quad \sum_{i=1}^{p} w_i = 100\,\%, \quad (4)$$

and gives the channel through which a given technique achieves its effect. The associated one-sample Hotelling statistic is $T^2 = n \cdot D^2$, which under multivariate normality is distributed as

$$\frac{n-p}{p(n-1)} T^2 \sim F_{p,n-p}\,. \quad (5)$$

Material

Mean values and standard deviations of eight variables — maximum bladder capacity, bladder wall thickness, effective urethral cross-section, post-void residual volume, mean flow rate, detrusor voiding pressure, detrusor muscular tension and the urethral resistance coefficient — were taken before and after operation for 142 boys with posterior urethral valves treated by endoscopic valve resection (group I, n = 32), polyethylene valvulotome ablation (group II, n = 49) or metallic valvulotome ablation (group III, n = 61).

Results

Component displacements and total separations are given in Table 1. The three techniques produced separations of comparable magnitude — 11.44, 12.20 and 13.09 standard-deviation units — with the metallic valvulotome largest and endoscopic resection smallest, a spread of only 14 % between the extremes.

Table 1. Component displacements $|d_i|$ and total separation D

Group	Q	p_{det}	S_u	K_u	V_r	T_d	h_w	V_{max}	D
I — endoscopic	7.62	5.72	4.25	2.61	2.32	2.88	1.20	0.44	**11.44**
II — polyethylene	3.15	2.93	8.50	6.01	3.77	2.21	1.70	0.15	**12.20**
III — metallic	1.96	9.59	6.33	3.80	3.54	2.18	1.58	1.08	**13.09**

The decomposition (4) tells a different story from the totals (Table 2, Figure 1). Although the three techniques move the patient a similar distance, they do so along markedly different directions. In group I nearly half of the squared separation is carried by flow rate (44.3 %) with detrusor pressure second (25.0 %). In group II almost half is carried by urethral cross-section (48.5 %), with the resistance coefficient second (24.2 %) and flow rate contributing only 6.7 %. In group III more than half is carried by detrusor pressure (53.7 %), with cross-section second (23.4 %) and flow rate almost absent (2.2 %).

Table 2. Contribution of each variable to the squared separation, %

Group	Q	p_{det}	S_u	K_u	V_r	T_d	h_w	V_{max}
I — endoscopic	**44.3**	25.0	13.8	5.2	4.1	6.4	1.1	0.1
II — polyethylene	6.7	5.8	**48.5**	24.2	9.6	3.3	1.9	0.0
III — metallic	2.2	**53.7**	23.4	8.4	7.3	2.8	1.5	0.7

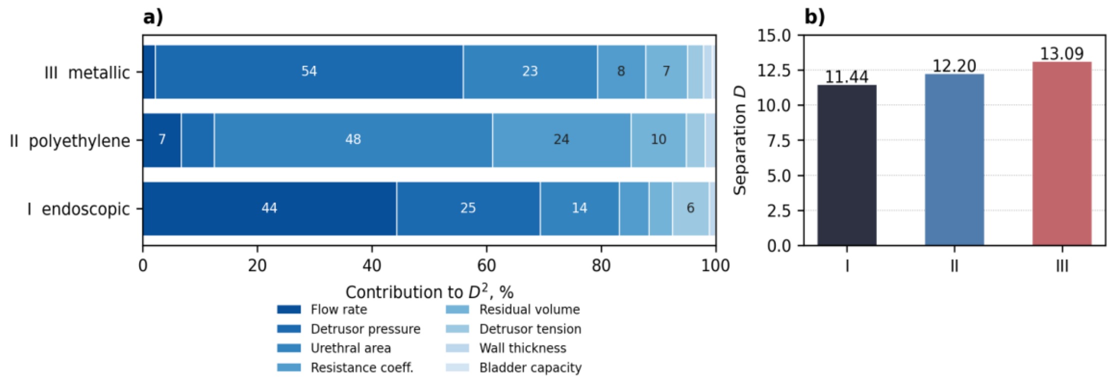

Figure 1. a) Decomposition of the squared separation into component channels; b) total separation D by technique.

Maximum bladder capacity contributed less than 1.1 % in every group. Removing it changes D by less than 0.05 units, confirming that it carries essentially no information about the relief of obstruction and can be omitted from a composite index of operative effect.

Discussion

Similar total separations reached through dissimilar channels have a direct interpretation. Group II achieves its displacement chiefly through the geometric variables — cross-section and resistance — with comparatively little change in flow or pressure, the profile expected when the outlet is widened but detrusor performance is unchanged. Group III achieves it chiefly through detrusor pressure, with the smallest flow-rate component of the three despite the highest absolute postoperative flow; this apparent paradox arises because the flow-rate displacement is divided by a pooled standard deviation inflated by the large postoperative dispersion in that group. Group I shows the most balanced profile but the smallest total.

The practical consequence is that a study powered on one endpoint may fail to detect the effect of a technique that acts through another. A trial using flow rate as its primary outcome would rank group I highest; one using cross-section would rank group II highest; one using detrusor pressure would rank group III highest. Reporting the decomposition alongside the total makes this dependence explicit.

The diagonal approximation is the principal limitation. Urodynamic variables are strongly intercorrelated, and neglecting the off-diagonal terms of Σ inflates the effective dimensionality, so the values of D reported here exceed the true Mahalanobis distances and should be used for comparison between groups rather than as absolute magnitudes. Because the same approximation is applied to all three groups, the ordering is preserved provided the correlation structure is similar across them — an assumption that individual-level data would allow to be tested. The component shares in (4) are affected less, since they depend on the ratios of squared displacements rather than on their absolute scale.

Conclusion

The three ablation techniques displace the urodynamic profile by similar total amounts ($D = 11.4$ to 13.1) but through different dominant channels: flow rate for endoscopic resection, urethral cross-section for the polyethylene valvulotome and detrusor pressure for the metallic valvulotome. Reporting the total separation together with its decomposition characterises an operative effect more completely than either a list of univariate tests or a single composite index, and shows which endpoint a comparative trial should adopt.

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