Research Paper

Three-Dimensional urethral profilometry - a global urethral pressure assesment method

Wioletta Katarzyna Szepieniec, Hanna Szweda *, Maksym Wróblewski, and Paweł Szymanowski

Department of Gynecology and Obstetrics; Andrzej Frycz Modrzewski Krakow University, Faculty of Medicine and Health Sciences, Krakow, Poland

* Correspondence: hanna.szweda@gmail.com

Abstract: BACKGROUND: To present a new method of urethral pressures examination, and to evaluate diagnostic capabilities of three dimensional profilometry, as an alternative to classical urethral profile (UPP). Using five channel catheters and dedicated software global urethral pressures image is obtained. The method eliminates the main limitation of classical urethral profilometry where the catheter orientation determines the pressures picture limited to only one point in the uretral circumference while we observed even 50% differences in pressure measures depending on the point of measurement. METHODS: This is a preliminary study containing method presentation and analisys of the use in varied clinical cases of either healthy patients and patients with LUTS. The article includes technique and equipment decription, full evaluation of selected cases, including three dimensional urethral pressures distribution graphics. RESULTS AND CONCLUSIONS:Three dimensional profilometry compared to classical technique is comparable regarding the time, cost, technical difficulty and patient discomfort. At the same time we obtain much more data on the urethral pressures and its distribution.The results are easy for interpretation due to 3D movable graphics created automatically through the dedicated software.

Keywords: urodynamics; urethral profile; urethral pressure; assessment method; profilometry

1. Introduction

In use since the 1970's, urethral profilometry (UPP - Urethral Pressure Profile) is one of several measurements utilized as part of a full urodynamic diagnosis. It does, however, have a number of limitations as a test in everyday clinical practice. One of these disadvantages is its low reproducibility. This limitation results from the use of traditional catheters which measure urethral pressure only from one direction of the urethral circumference. The anatomical structure of the urethra means that the dimensional pressure distribution is very different depending on the direction from which the measurement is taken. In patients who have a pathology of the lower urinary tract, or who have had surgery or injuries in this area, this variation in pressure distribution is impaired.

The study presented in this paper allows for the assessment of urethral pressure (Pura) along the entire length of the urethra. Pressure readings are taken at the same time in 4 directions radially every 90° with simultaneous measurement of the intra-bladder pressure (Pves).

Three-Dimensional profilometry allows for more precise and global assessments of the peripheral pressure distribution in the urethra. This type of measurement results in the elimination of the effects of the catheter being rotated or imprecisely placed during examination which can very often produce false readings. By using the Three-Dimensional profilometry, the imperfections of classical urethral profilometry are reduced or even totally eliminated.

Urinary incontinence or involuntary urination, which is so prevalent in the world that WHO qualifies it as a social disease, can occur at any age, but it is most common among elderly population, twicely more common in women than in men [1].

In the majority of patients, however, it is a chronic symptom which can be completely cured or reduced after a proper diagnosis.

As many as 50% of women between the ages of 45 and 60 have experienced an incontinence incident [2] One of the main risk factors of urinary incontinence is childbirth (stress urinary incontinence is diagnosed up to 30% after physiological delivery and up to 31% after delivery by forceps) [3].

A common method of assessing the function of the urethra in stress urinary incontinence is profilometry, although this method is often criticized for its poor repeatability. [4]

Current methods used to measure urethral pressure utilize different types of catheters Regardless of the type, measurement of urethral pressure with one channel catheter does not give the opportunity to detect any assymetries in pressures distribution [5].

Catheters recommended for measurement of urethral pressure by the International Continence Society (ICS) are water-perfused systems. These are considered to be the most accurate and allow researchers to obtain reproducible and comparable results in contrast to micro-tip or air-filled catheter systems. [6, 7]

At the same time, ideal methods for differentiating continent patients from stress incontinent are still searched, and there is also a lack of tools for assessing the treatment methods based on pathophysiological changes in the urethra.

The urethra is not a symmetrical thick tube. Pressures in different points of its circumference differ significantly [8,9], which results from the urethra and pelvic floor anatomy and function. Urethral sphincter has a horseshoe shape opened dorsally. What is more, the shape, functional length, stiffness, and mobility of the urethra, are defined by other pelvic floor structures surrounding urethra on its different levels. Classical urethral profile measurement is taken along the urethra, but from only one point of urethral circumference.

In a view of these shortcomings when using traditional methods to measure the urethral pressure, it is desirable to perform measurements over the entire length and whole circumference of the urethra. An advantage of these measurements over their classical counterparts is their reproducibility and independence from examination eg. cough test. [10,11]

The purpose of this pilot study using the system described below is to evaluate a method of measuring urethral pressure changes more accurately, regardless of the peripheral position of the sensors in the urethra. Three-Dimensional profilometry allows to create picture of pressures distribution along the whole urethra and around its whole circumference. The conception is based on the methodology of anal sphincter manometry, extrapolated on urogenital tract conditions. In the 1990's there were some in vitro trials of this kind of urethral pressure assessment [9] and also attempts to use the method in animals appeared promising [12,13]. Regarding these data, in our work we have skipped the biophysical and in vitro testing stage. We used the idea of anal sphincter manometry, which has been used in clinical practice for years. [9,12,13] Seeing its potential in clinical practice we performed, as a pilot study, the examination in women. A further purpose of this work is to present a three-dimensional approximation of pressure distributions in the urethra in order to better understand the mechanisms of incontinence. The technique of either classic and three-dimensional profilometry requires the use of a special catheter and puller which is an integral part of urodynamic devices. The catheters used do not differ from the standard stiffness but are slightly thicker than the most commonly used catheters (9Fr vs 8Fr; catheter sizes of up to 10Fr are allowed according to ICS recommendations) and the examination technique is the same as in the classic urethral profilometry. Additionally to 3D profilometry we use special software. The time of the assessment and its complexity does not differ from the classical method. It takes less than 10minutes, which considering the whole complex urodynamic study seems to be a short time added. The main difference is the number of sensors used and, hence, the amount of data collected. Thus, it can be assumed that the idea of the test, either as patient discomfort, tolerance, and duration of the examination will not differ from those when using the classical method. Thus, using the 5 channel catheter and dedicated software, the performance doesn't differ neither for the investigator,nor for the patient. However the amount of data collected during the test three-dimensional profilometry is significantly greater when compared to the conventional method. [14] Regarding the reproducibility of three dimensional UPP we already started the reproducibility trial as the next stage of our studies on the method. However, reports from 1997 are promising and showed high reproducibility of multichannel profile measurements. [15] Further research on a larger group of patients is needed also to describe the characteristics of three-dimensional profilometry for specific pathologies. We continue the research fullfilling these expectations.

2. Materials and Methods

Settings and participants

The research was carried out in the Department of Gynecology and Urogynaecology at the Andrzej Frycz Modrzewski Krakow University from June 2018 to October 2018. The measurements were performed on a group of 25 women presented in the clinic for the treatment of urinary incontinence or after previous pelvic floor repair surgery or mid-urethral tape operations. The study included symptomatic as well as asymptomatic patients. The control group consisted of patients who did not report problems related to urinary incontinence or other disorders within the pelvic floor (4 patients). All patients were at least 18 years old, not pregnant, showed no significant prolapse of the pelvic organs of more than POP Q 1. The patients in the control group, without any symptoms of urinary incontinence, showed no signs of SUI either in the questionnaire or in the cough test, and had not previously undergone any surgery due to urinary incontinence or pelvic floor repair. The patients in the incontinence group were patients either with clinical symptoms during examination or with symptoms of mixed incontinence or overactive bladder. Asymptomatic as well as symptomatic patients after surgery due to SUI or pelvic floor repair were also included in this group**.** The questionnaire presented to patients included the following information: age, height, weight, BMI, gynecological operations, parity, types of childbirth, weight of the largest child, whether they smoked and family history of urinary incontinence. They filled out a short form for Incontinence Severity Index (ISI, scale 0-12).

The patients who took part in the study were volunteers and were not associated with the authors in any way.

Measurement

The examination were conducted according to the standards published in Neurology and Urodynamics [7].

Urethral pressure measurements

After micturition a Foley catheter 12 or 14 Fr is used to empty the bladder of residual urine. Next,using the catheter, the bladder is filled with 200 ml of sterile water at room temperature or slightly warmer. In patients with reduced bladder capacity the bladder is filled to the maximum volume that does not cause discomfort for the patient. After removal of the catheter a cough test is performed to confirm the absence or presence of leakage of urine. While the patient is in a semi-sitting position the catheter is inserted into the urethra to a depth guaranteeing that all the sensors are in the bladder. In order to confirm that the catheter has been accurately placed a cough test is again performed. The auxiliary line on the catheter (indicating channel Pura1) should be directed ventrally. The catheter is then attached to a pulling mechanism which is used to pull the catheter out. The speed of the catheter withdrawal in each case was 1 mm / s. The resting urethral profile is performed twice on each patient and the stress (dynamic) profile is performed once.

System for urodynamics PICO SMART

Measurements collected from the tests were processed using a computerized system for urodynamics, **PICO SMART**, software **PICO3000** version **6.11.**, manufactured by **MEDICA S.p.A.**, MODENA – ITALY.

The system was supplied with pressure modules **SAU-LG** (sampling rate - 100 Hz per channel; measuring range from -100 up to +540 cmH2O; sensitivity: 0,15 cmH2O; accuracy 1% of full scale) with 5 independent pressure transducers **MX960P1**.

The profile was performed with a 5-way water perfused catheter **(5PPV-9)** which was custom designed and manufactured by **MEDICA S.p.A**., MODENA – ITALY**.** The catheter is fitted with a central lumen which is 1.1 mm in diameter with an opening at the tip for measurement of vesical pressure "Pves" and 4 lumens with 4 side-port openings of 0.8 mm in diameter, 6.0 cm apart from the central lumen. The side ports are radially arranged every 90° to measure urethral pressure "Pura" simultaneously from 4 different directions. The external diameter of the catheter is 9 Fr (3 mm), with a cannula length of 400 mm, and it is made of medical grade PVC.

The catheter is equipped with 5 extension lines 180 cm in length which connect the catheter to pressure transducers.

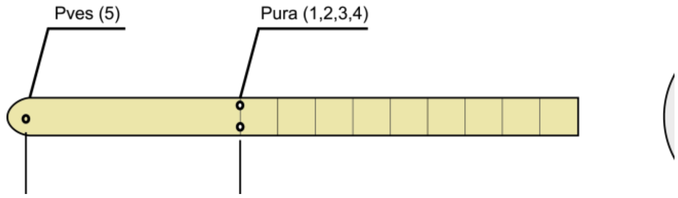

Figure 1. Placement of lumens in catheter 5PPV-9.

In order to achieve normal perfusion of the urethral channels while the measurements were taken, the Quadruple Capillary set (**QCI**) powered by a cuff pump was used, and equal perfusion of 1 ml/min for all urethral channels was obtained because of this capillary set.

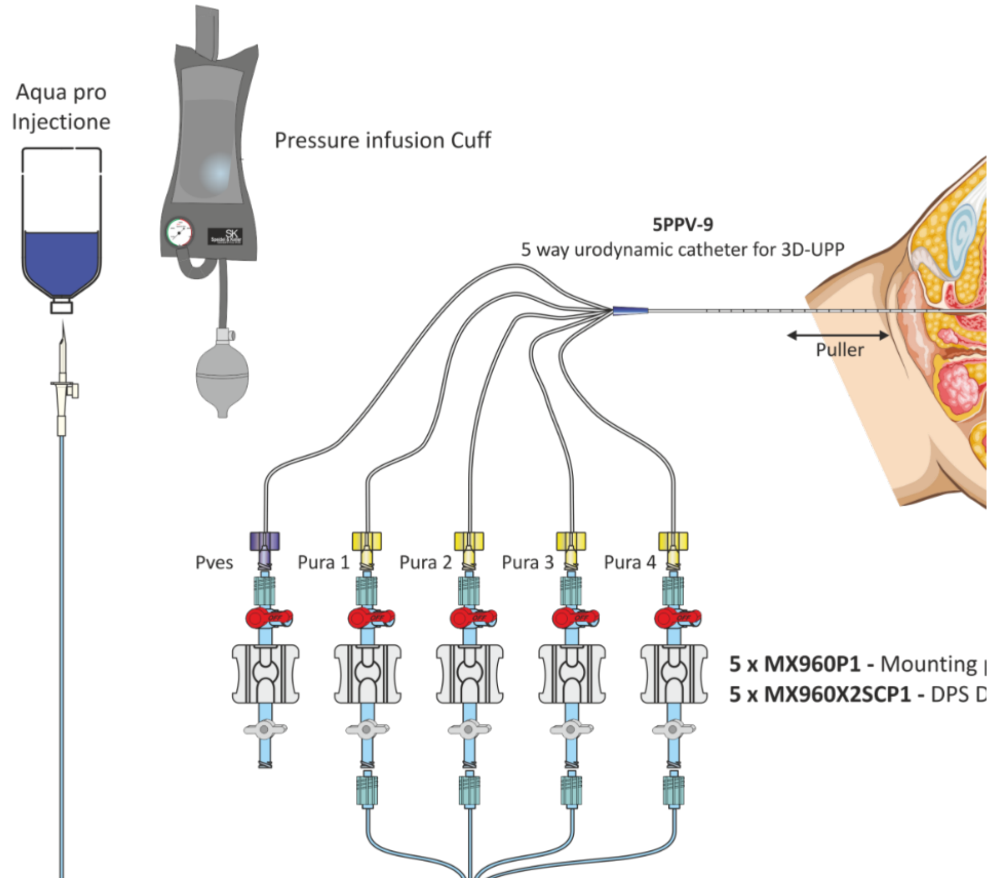

Figure 2. Connection diagram.

Static UPP with 3D presentation.

Analysis of the static UPP is performed on each graph of Pura pressure.

Static UPP automatically places the following markers:

F1 marks the onset of the profile (start of the high pressure zone, beginning of the functional length).

F2 marks the top of the curve (Pura max)

F3 marks the end of the profile curve where the pressure returns to bladder values. It marks the point in which the catheter has passed through the striated sphincter. It is at this point that the profile functional length is calculated as the length of the urethral section where the pressure is higher than in the bladder.

Static UPP report shows the following details for each measured channel (direction):

- **Ev**: is the number of profiles being measured.
- **P_ves**: Pressure in the bladder.
- **P_ura max**: Maximum urethral pressure measured in relation to marker F2
- **P_ucp**: maximum urethral closure pressure defined as P_ura max -P_ves
- **P-ave** : average urethral pressure
- **L_pmax**: Length of maximum pressure, in other words, the distance in mm between the maximum pressure point and the start of the high pressure zone (F2-F1).
- **L_fun**: functional length, in other words, the length of the section where the pressure is higher than the bladder pressure (F3 – F1).
- **Area**: continence area. This is the area under the profile curve from marker F1 to marker F2. Dimensional analysis results in the following:

  [Pressure]*[Length]= MT^{-2} mass divided by time squared.

  [Energy] / [Surface] = MT^{-2} Continence area has dimensions similar to energy per surface unit and represents the potential energy associated to the urethral sphincter strictly related with the urethral competence. The meaning of this parameter has not yet been fully explained.
- **Vector volume**: continence volume calculated from areas along the functional length of the urethra.
- **TLS**: Total Length of the Sphincter.

Vector Volume

The analysis window presents a three-dimensional representation of the Vector Volume with the following information:

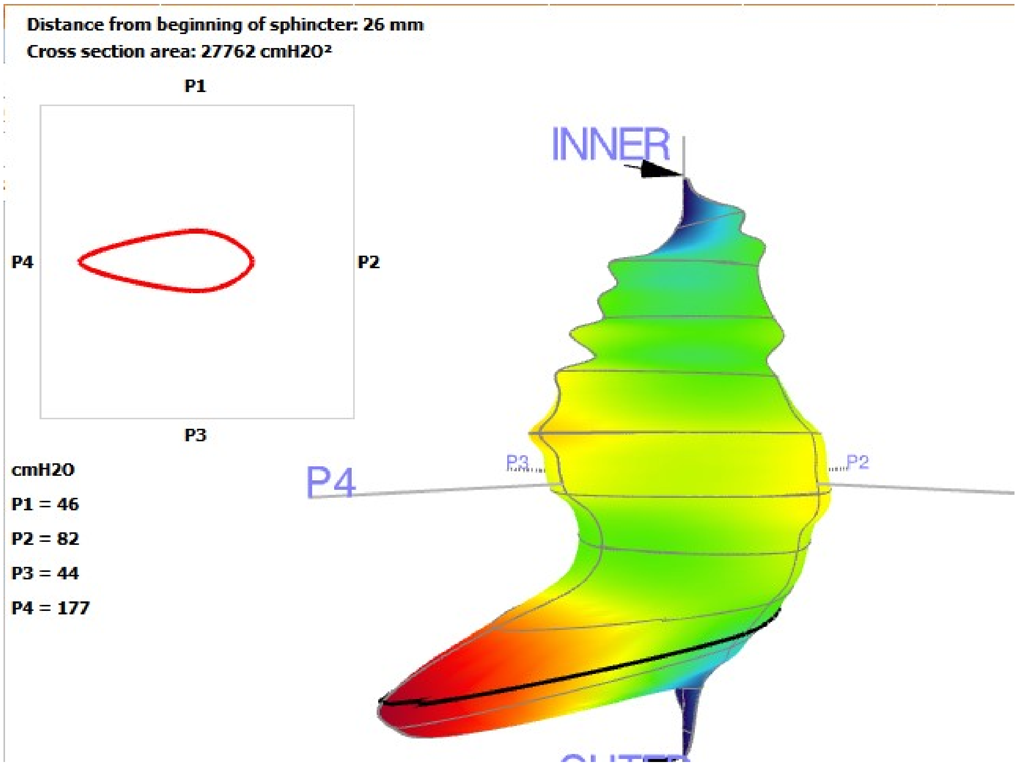

Figure 3. Cross section of the Vector Volume in correspondence with the distance from the beginning of the sphincter.

The area is calculated by the following formula:

Area = 0.5[(P1xP2)+…….(Pn-1 x Pn)+(Pn x P1)]sin ◎[in cmH2O²]

This represents the area of the polygon whose vertexes are P1,….Pn. The angle ◎ between the vertices is 2π/n.

The scrolling bar on the graph allows the black vertical cursor to be moved thereby changing the distance from the beginning of the sphincter. The pressures shown on the 3D graph and area values correspond with the position of the cursor.

One of the functions of the software is that the picture can be rotated by the scrolling buttons on the lower left side and screenshots can be taken by using the image buttons. These can then be inserted into the medical report.

Dynamic UPP.

The analysis of the dynamic UPP is performed on a selected graph showing Pura pressure. It can be performed separately for each direction. The Dynamic definer has the following markers:

Pves channel:

F1 at the foot of each peak .

F2 corresponding to Pves peaks

Pura channel:

F1 at the foot of each peak

F2 at the top of Pura peaks

The program computes a data report with the numerical values of P_ura measured in correspondence to markers F1.

Furthermore it shows the distance of every event (peak) from marker "d" and the value of the transmission coefficient at every peak, defined in the following way:

T.C.% = 100(F2-F1 at Pura)/(F2-F1 at Pves)

Urethral pressure profile is a test indicated for the evaluation of incontinence. As an indication the normal value of urethral closure pressure can be derived by the formula 110-age in which values less than 20 or 25 cmH2O are surely pathological.

For dynamic UPP, values of TC less than 80 are considered pathological.

3. Results

Below we present examples of the three-dimensional profilometry evaluations according to above mentioned scheme.

Patient: G-001 **Age (at examination): 28 years**

Examination date: ***18.04.2018*** *Prot.* ***A - UPP S VETTORE*** **Puller:** 1,0 mm/s

History: healthy control group patient without incontinence

Resting profilometry

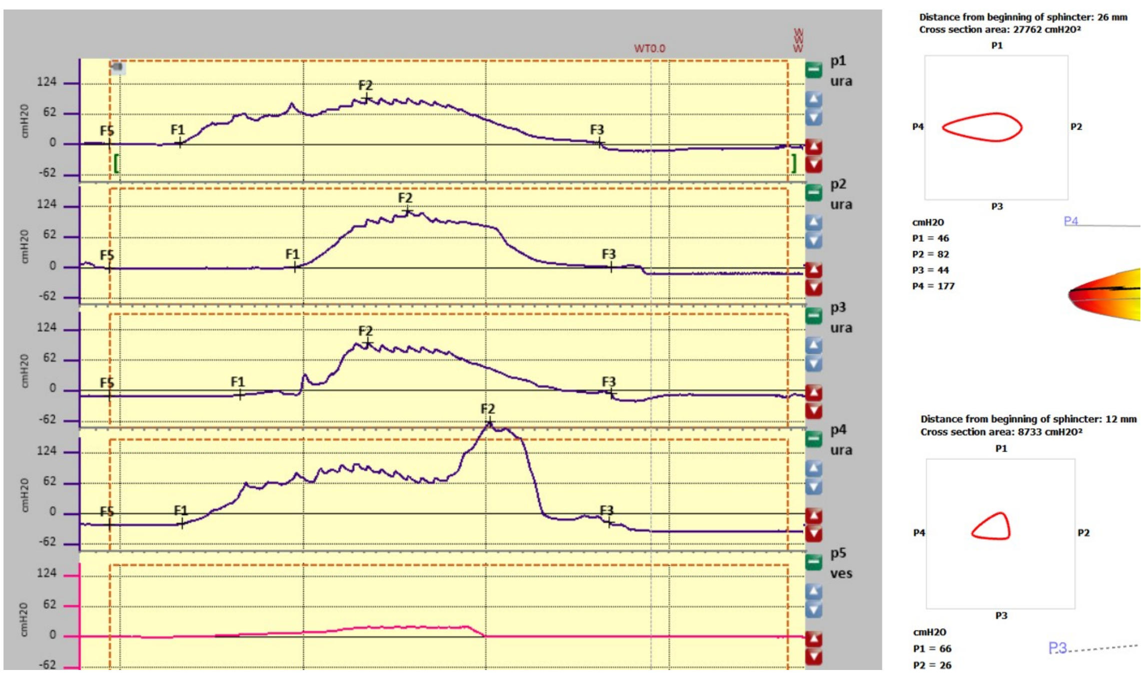

Fig. 4

Ev	P_ves (cmH2O)	P_ura max (cmH2O)	P_ucp (cmH2O)	P_ave (cmH2O)	L_pmax (cm)	L_fun (cm)	Area (J/m^2)	VV (cmH2O ^2*mm)	TSL (cm)

p1 ura	19,9	94,5	74,5	51,8	1,5	3,4	84,0	255800,0	3,5
p2 ura	20,2	114,6	94,4	56,5	0,9	2,6	58,0		
p3 ura	19,9	95,9	75,9	47,4	1,1	3,0	35,0		
p4 ura	1,3	186,9	185,7	86,1	2,5	3,5	224,0		

Table 1

There were significant differences in the functional length of the urethra (upper right side - 3.5 cm, bottom left side - 2.6 cm). Pura max was around 100 cmH2O except for a peak increase at a distance of 26 mm from the internal sphincter on the right. This increase may suggest compression (obstacle) in this region. In the middle region of the urethra uniform pressure distribution in the range of 80 cmH2O is observed. The maximal closure pressure of the urethra in all directions above 94 cmH2O is higher than the values typical for the patient's age (110 - age [28] = 82 cmH2O). What draws attention in this profile is a high difference between P ura max values in different directions- 92,4 cm H2O between p4 and p 1, which is 50,5% in an asymptomatic patient.

Stress profilometry

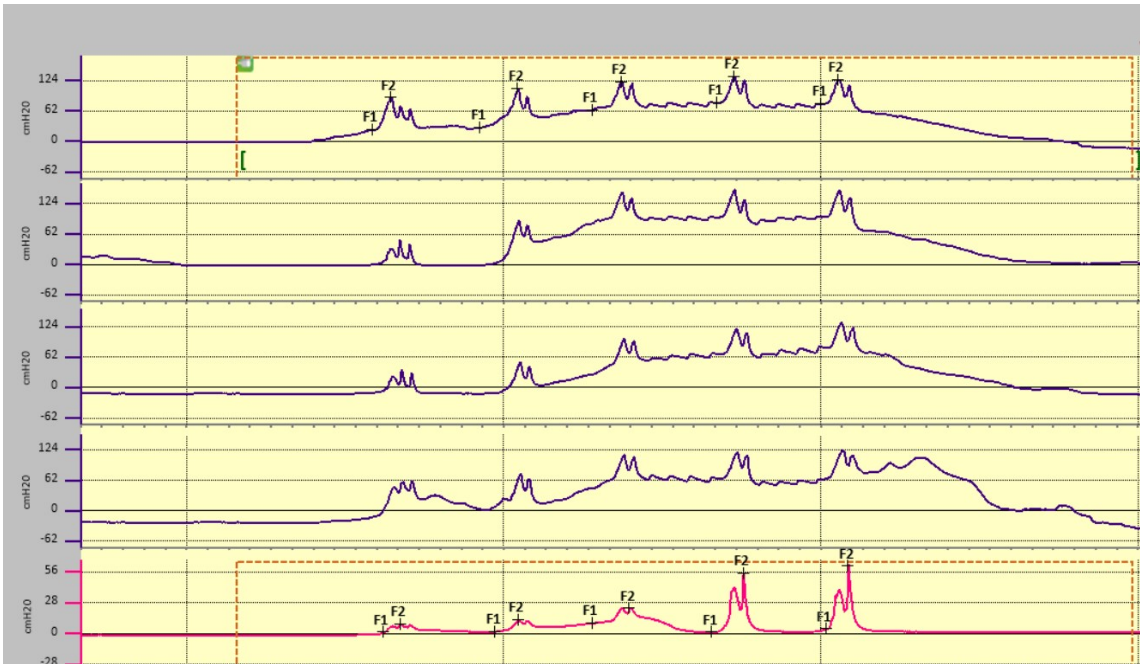

Figure 5.

Profile.	**P_ura in F1** *(cmH2O)*	**Pucp in F2** *(cmH2O)*	**Distance from 'd'** *(cm)*	**T.C.** *(%)*
Peak 1	63,1	98,6	1,86	601,11
Peak 2	77,7	76,7	2,40	100,28
Peak 3	75,3	63,5	2,89	86,30
			Average transmission rate:	**262,57**

Table 2

In provocation tests, positive closure pressures have been demonstrated over the entire length of the urethra. However, these values caused by provocative tests (cough pulses) do not exceed 40% of the average static closure pressure of the urethra. For a proper evaluation of the stress test (dynamic) it is recommended that provocative tests (cough impulses) reach about 80% of the average static closure pressure of the urethra. A high transmission coefficient T.C. (262.57%) is much higher than the value below which possibly represents the presence of pathological changes.

Patient: **G-002** **Age (at examination): 45 years**

Exam. nr: ***29*** *Exam date::* ***21.08.2018*** *Prot.* ***A - UPP S VETTORE*** **Puller:** 1,0 mm/s

History: Healthy patient without incontinence

Rest profilometry

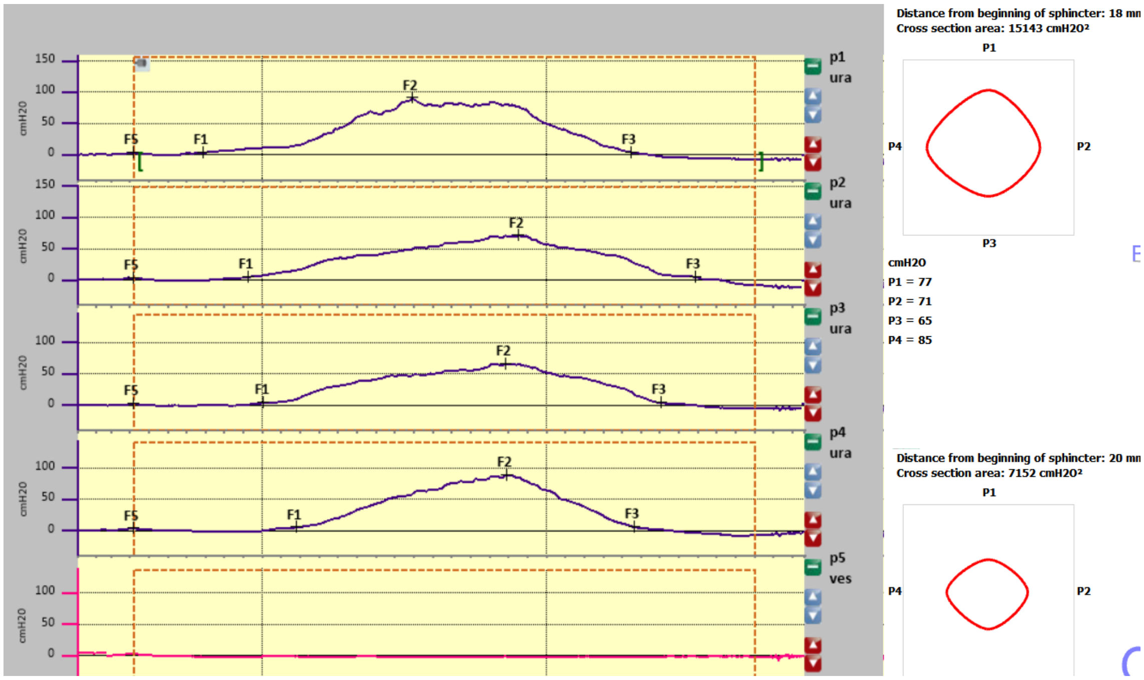

Fig. 6

Ev	P_ves (cmH2O)	P_ura max (cmH2O)	P_ucp (cmH2O)	P_ave (cmH2O)	L_pmax (cm)	L_fun (cm)	Area (J/m^2)	VV (cmH2O ^2*mm)	TSL (cm)
p1 ura	-1,8	90,4	92,2	42,4	1,1	2,3	32	99560,30	2,6
p2 ura	-1,3	70,8	72,1	34,4	1,4	2,4	50		
p3 ura	-1,0	66,5	67,5	36,2	1,3	2,1	45		
p4 ura	-1,3	88,9	90,2	44,2	1,1	1,8	49		

Table 3

Slightly smaller functional length of the urethra on the right (Pura4). Peripheral Pressure distribution is uniform. Maximum urethral closure pressures in all directions above 66 cmH2O correspond to the values typical for the patient's age (110 - age [45] = 65 cmH2O)

Stress profilometry

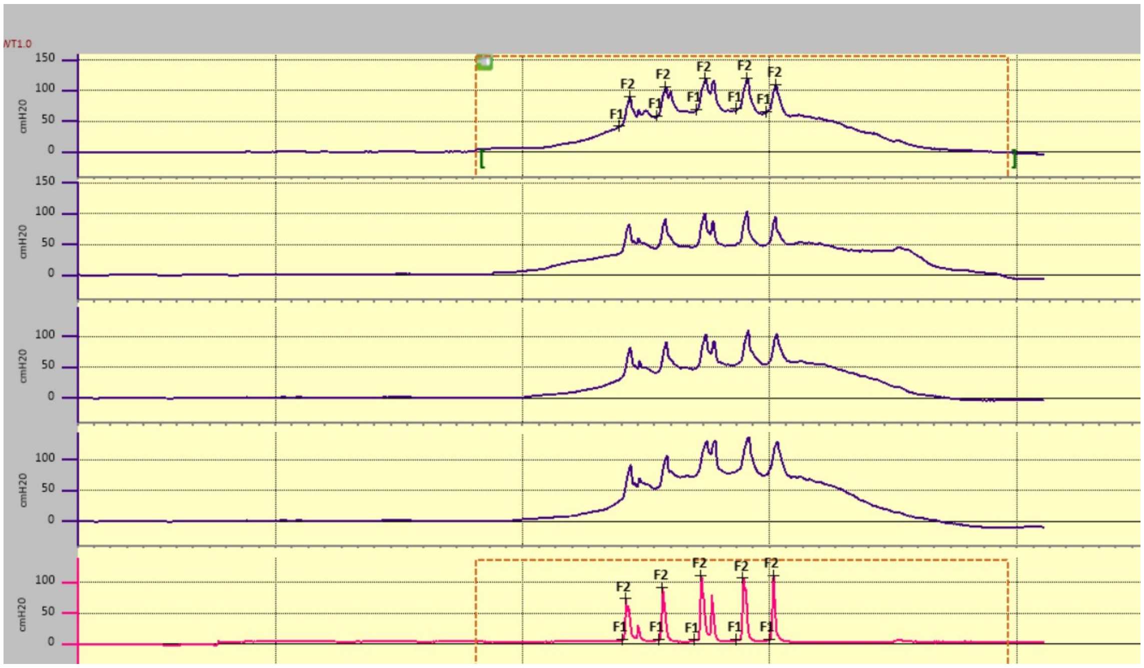

Fig. 7

Profile	P_ura in F1 *(cmH2O)*	Pucp *(cmH2O)*	Distance from 'd' *(cm)*	T.C. *(%)*
Peak 1	41,5	17,3	0,93	73,33
Peak 2	58,4	14,7	1,15	56,20
Peak 3	68,7	7,4	1,39	47,32
Peak 4	69,9	13,2	1,65	50,18
Peak 5	64,2	-1,0	1,82	43,,6
			Average transmission rate:	**54,08**

Table 4

Despite intense provocative tests, (cough pulses) of more than 130% of the average static closure pressure, in provocative tests, closure pressure do not reach negative values over the entire length of the urethra. A transmission coefficient T.C. (54.08%) lower than normal may indicate susceptibility SUI.

Patient: **G-006** **Age (at exam.):** **51 years**

Exam. nr.: **32** *Exam. date:* ***25.05.2018*** *Prot.* ***A - UPP S VETTORE*** **Puller:** 1,0 mm/s

History: **patient with symptoms of stress urinary incontinence qualified for operation**

Rest profilometry

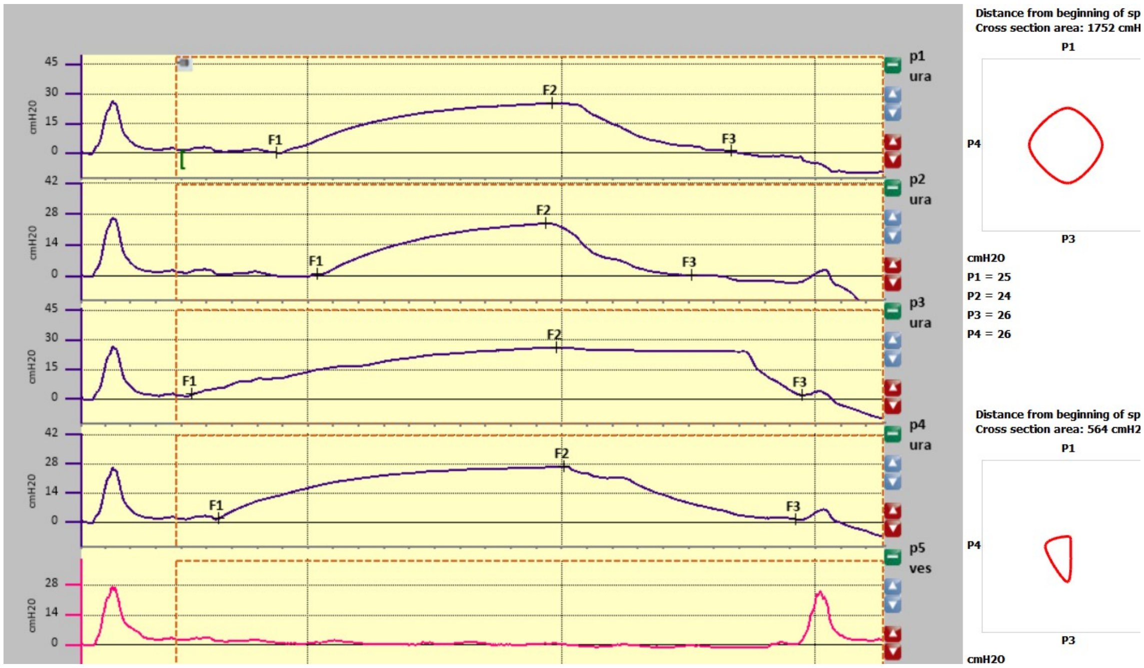

Fig. 8

Ev	P_ves (cmH2O)	P_ura max (cmH2O)	P_ucp (cmH2O)	P_ave (cmH2O)	L_pmax (cm)	L_fun (cm)	Area (J/m^2)	VV (cmH2O ^2*mm)	TSL (cm)
p1 ura	2,8	25,4	22,6	15,4	1,0	1,6	17	11514,7	2,3
p2 ura	2,7	23,8	21,1	14,5	0,8	1,2	13		
p3 ura	2,7	26,3	23,6	17,5	1,4	2,3	21		
p4 ura	2,4	26,5	24,1	17,5	1,3	2,0	25		

Table 5

Significant differences in the functional length of the urethra (top and right side - 1.8 cm, bottom and left side - 2.4 cm). Pura max is around 26 cmH2O. In the central region of the urethra, the pressure distribution is equable at around 20 cmH2O. At a distance of 19 mm from the internal sphincter, urethra functionality is preserved only from the direction Pura3 (bottom), in all other directions a rapid decrease in pressure readings is observed. The maximal closure pressure of the urethra in all directions below 26 cmH2O does not reach the values typical for the patient's age (110 - age [51] = 59 cmH2O).

Stress profilometry

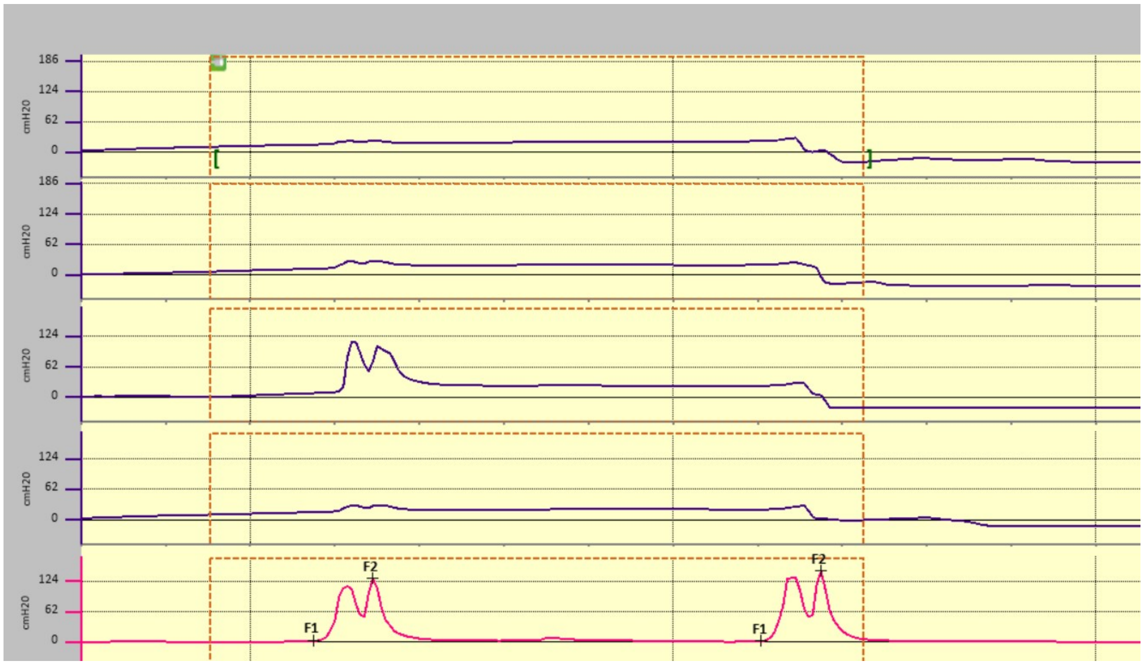

Fig. 9

The patient failed to perform proper stress profilometry. Any provocation test triggered immediate leakage of urine. A provocative test that increases the pressure inside the bladder to the value of 120 - 130 cmH2O did not increase the urethral pressure in the directions P1, P2 and P4, therefore the analytical markers for these channels could not be located. Only in the P3 direction (rectum) at the very proximal part of the urethra was there an increase in pressure up to 72 cmH2O, but it was not sufficient to cause urethra closure. Closure pressure for this direction was negative (-57 cmH2O).

Patient: **G-010** **Age (at exam.):** **79 years**

Exam. nr.: ***37*** *Exam. date:* ***27.07.2018*** *Prot.* ***A - UPP S VETTORE*** **Puller:** 1,0 mm/s

History:Patient after effective SUI surgery, asymptomatic

Resting Profilometry

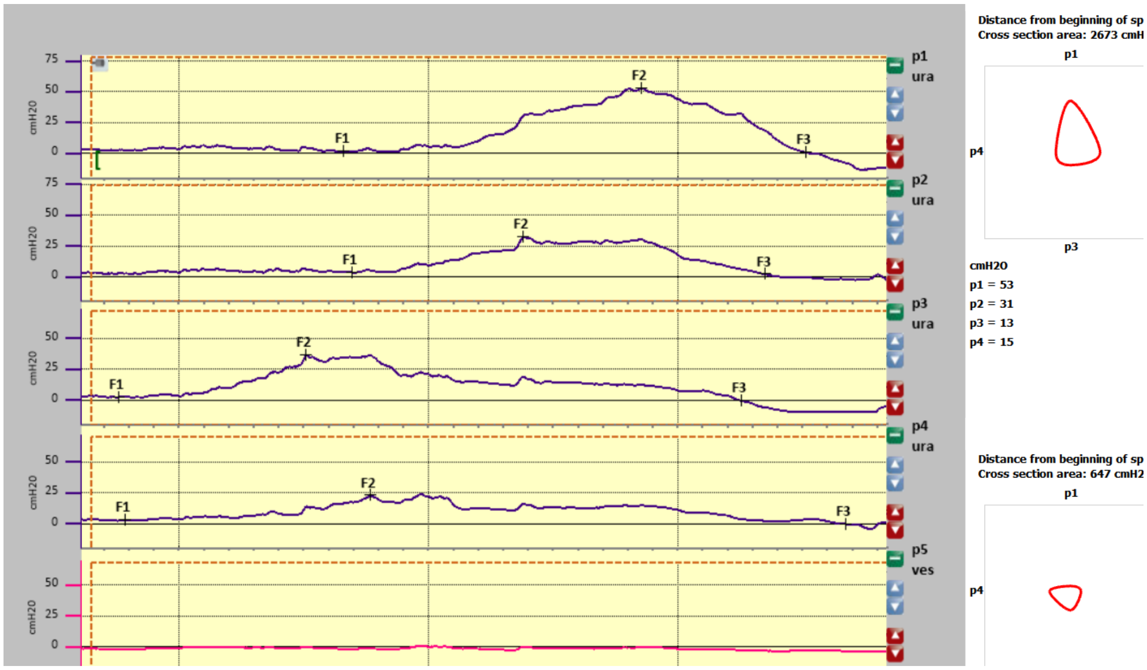

Fig. 10

Ev	P_ves (cmH2O)	P_ura max (cmH2O)	P_ucp (cmH2O)	P_ave (cmH2O)	L_pmax (cm)	L_fun (cm)	Area (J/m^2)	VV (cmH2O ^2*mm)	TSL (cm)
p1 ura	-0,1	52,8	52,9	23,1	1,2	1,9	22	12395,9	2,9
p2 ura	-0,1	32,4	32,5	14,5	0,7	1,7	6		
p3 ura	-0,4	36,7	37,1	13,5	0,8	2,5	7		
p4 ura	-1,1	22,6	23,7	8,2	1,0	2,9	5		

Table 6

The pressure distribution on the periphery is asymmetric with a significant displacement of approx. 10 mm of the functional part of the urethra from the direction Pura 1 (top) and Pura2 (left). Pura3 (bottom) and Pura 4 (right) shows a large difference in the functional length of the urethra between these directions with a marginal pressure reading from Pura4 (right) up to 22.6 cmH2O. In the lateral directions of Pura2 and Pura4, there is a large displacement of the pressure Pura max. The distance between F2 markers is about 14 mm. In the central part of the urethra the symmetrical pressure distribution, however, does not exceed 20 cmH2O. Maximum urethral closure pressure typical of the patient's age group (110 - age [79] = 31 cmH2O).

Significant difference between p1 and p 4 values of P ura max (52,8 vs 22,6 which is 57%

Stress profilometry

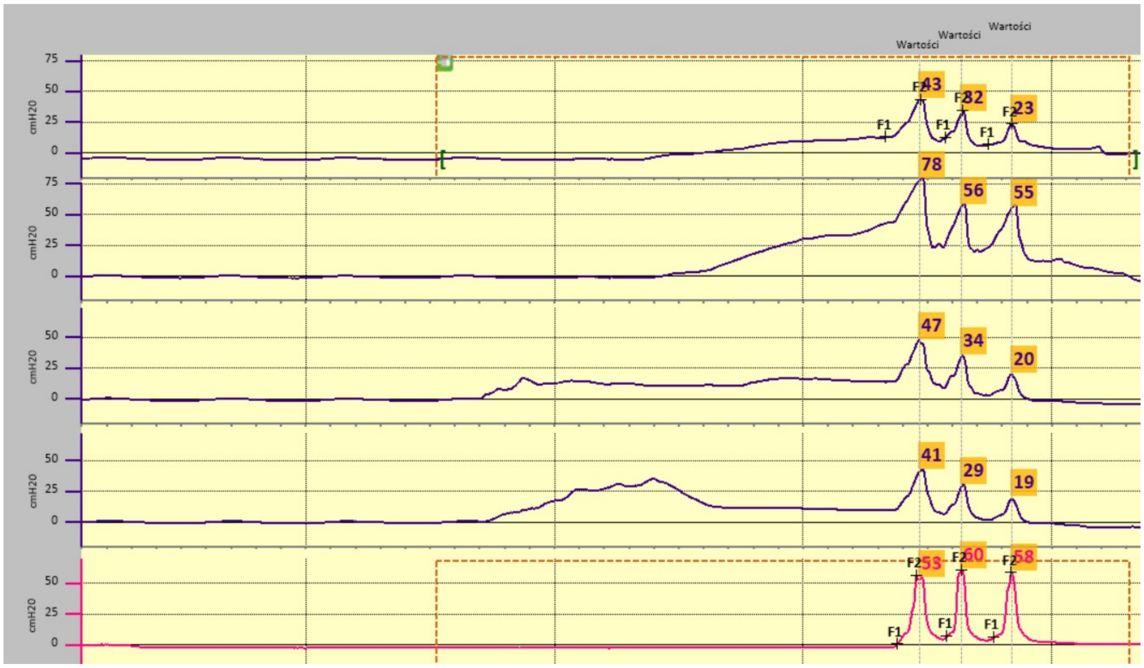

Fig. 11

Provocative tests (cough pulses) in the range of 160% of the average static urethra closure pressure are adequate for the correct evaluation of stress profile.

Profile *(for Pura1)*	**P_ura in F1** *(cmH2O)*	**Pucp in F2** *(cmH2O)*	**Distance from 'd'** *(cm)*	**T.C.** *(%)*
Peak1	12,8	-12,9	1,95	54,77
Peak2	12,0	-26,0	2,12	42,01
Peak3	6,4	-35,0	2,31	32,41
			Average transmission rate:	**43,07**

Table 7

In the basic dynamic analysis of Pura 1 direction (up) the urethral closure pressure in provocative tests on the entire length of the urethra reaches negative values, which confirms the existence of SUI. A low transmission coefficient of T.C. (43.07%) indicates the occurrence of pathological changes.

A dynamic analysis of Pura2 (left side) of the urethral closure pressure during the provocative test shows positive values or slightly below 0, indicating a lack of SUI.

Profile (for Pura2)	P_ura in F1 (cmH2O)	Pucp (cmH2O)	Distance from 'd' (cm)	T.C. (%)
Peak1	44,1	24,0	1,95	64,67
Peak2	25,5	-1,9	2,12	61,91
Peak3	24,1	-0,8	2,33	64,06
			Average transmission rate:	**63,55**

Table 8

A much higher transmission coefficient T.C. (63.55%), however, still indicates the occurrence of pathological changes.

Averaged urethral closure pressure for all provocative tests is negative, indicating that the patient has SUI.

The average transmission coefficient T.C. (47.96%) also indicates the occurrence of pathological changes.

A lack of discomfort associated with SUI may be the result of a lateral collapse of the urethra which is visible in the static profile.

Patient: **G-011** **Age (at exam.):** **73 years**

Exam. nr.: ***9*** *Exam. date:* **25.05.2018** *Prot.* ***A - UPP S VETTORE*** **Puller:** 1,0 mm/s

History: **Patient after several incontinence operations still suffering from incontinence**

Rest profilometry

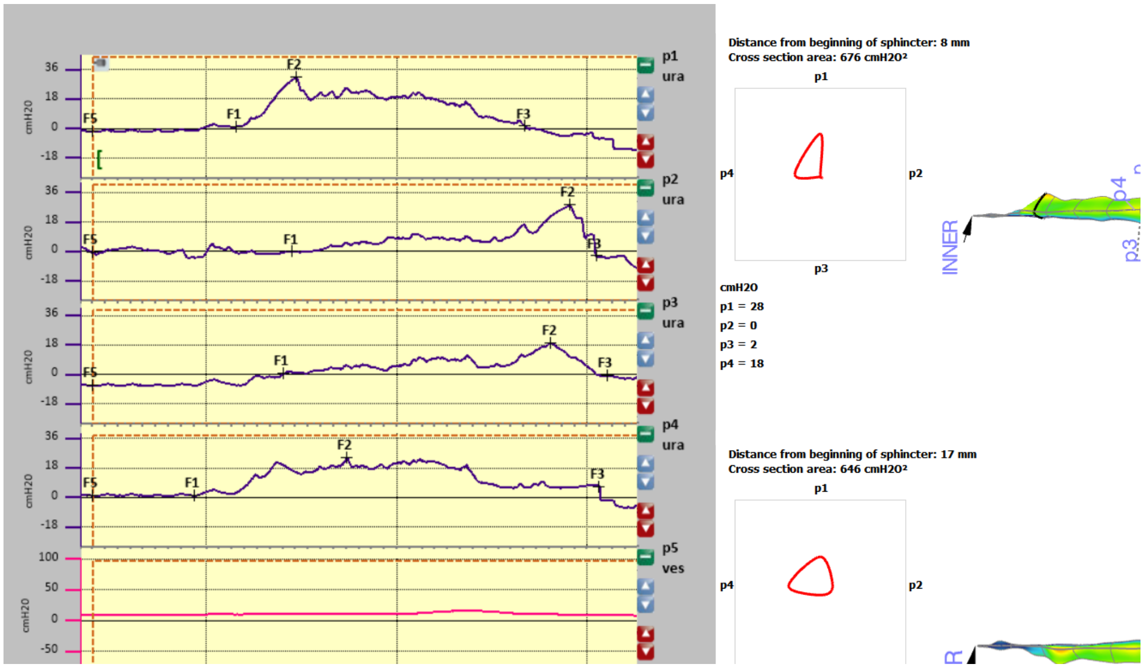

Fig. 12

Ev	P_ves (cmH2O)	P_ura max (cmH2O)	P_ucp (cmH2O)	P_ave (cmH2O)	L_pmax (cm)	L_fun (cm)	Area (J/m^2)	VV (cmH2O ^2*mm)	TSL (cm)
p1 ura	10,8	31,3	20,6	15,8	0,5	2,3	6	6008,1	3,3
p2 ura	9,4	28,1	18,7	8,9	2,2	2,4	17		
p3 ura	10,1	18,9	8,8	6,8	2,1	2,6	13		
p4 ura	11,2	8,0	-3,2	10,9	1,2	3,2	11		

Table 9

The distribution of peripheral pressures along the entire length of the urethra is asymmetric. The Pura max position is observed to have moved over 11 mm between the Pura 1 and Pura 2 and 3 channels. The bottom and left directions are active after finishing the profile in the remaining directions.

The maximal urethral closure pressure does not reach the values typical for the patient's age (110 - age [73] = 37 cmH2O).

Stress profilometry could not be performed due to the significant degree of SUI.

The examinations which were performed using the dimensional profilometry method were well-tolerated by patients. The catheter, despite its specificity, did not cause discomfort to patients. The time needed to perform the tests was on average 2 minutes for tests at rest and 2 minutes for stress profilometry. The time necessary to conduct dimensional profilometry was not any longer than classical urethral profilometry.

4. Discussion

The present study resulted in the collection of detailed data on pressure distribution within the urethra and the main limitations of classical urethral profilometry were eliminated by the use of 4-channel catheters. The differences in pressure readings depending on the position of the catheter measurement channel in classic profilometry can be significant. The 5PPV 9 catheter used in the method presented in this paper has 4 marked Pura measuring channels. In patients with SUI the average pressure difference between the channels with the highest and lowest pressures was 32.45 cm of water. Performing urethral profilometry four times using a classical catheter and changing the position of the measuring channel every 90 degrees would not get comparable results, due to changes in the muscle tonus of the pelvic floor and the tonus of the sphincter during subsequent tests. Simultaneous measurement at 4 points around the circumference of the urethra results in a significant advantage of dimensional profilometry over the traditional method. It was also discovered that in asymptomatic patients (see G 001) there may be significant pressure differences in the urethra. Here, it would be necessary to further investigate the impact of pregnancy and the mode of delivery (vaginal vs. cesarean section) on the function of the urethra. Studies should be carried out on female patients undergoing elective caesarean section, because only by assessing this group of patients would the evaluation of the possible impact of pregnancy on the functions of the urethra be properly studied.

It is interesting that depending on the location of the measurements taken regarding individual channels, differences in the functional length of the urethra were also found, with the P3 channel being the most variable indicator. In patients with stress urinary incontinence (8 patients in the database) 3 patients had the longest Lfun in channel P3, and in 4 patients the shortest Lfun was in channel P3. The average difference between the longest and the shortest Lfun in these eight patients with SUI is 1.01 cm.

Another conclusion worthy of consideration applies to the analysis of test subjects who had undergone successful stress urinary incontinence surgery using a mid-urethral sling TOT. This is particularly evident in asymptomatic patient G-010 who was operated for SUI, negative pressures occur in the P1 channel over the entire length of the urethra. Such results could confirm the fact that the effectiveness of a mid-urethral sling does not require the correction of pressures over the whole circumference of the urethra.

In patients who were examined with stress urinary incontinence , there is no clear tendency to maximum and minimum pressure values in specific directions of measurement.

A valuable parameter obtained during exercise profilometry is the so-called Transmission Coefficient (TC), which illustrates the transmission of pressure during provocative tests. It seems that the lower the TC, the higher the risk of pathological changes of stress urinary incontinence. This is clearly visible in patient G006, with SUI and low pressure in the urethra, where the TC amounted to only 25%.

TC is also lower in patients with initially high resting urethral pressures, which may indicate the impact of excessive tension of the pelvic floor on the function of the urethral sphincter. This can be seen in the final reading of the stress profile in patient G 001 who has a high TC over the entire length of the urethra, with a significant decrease in TC during the last cough test in a place where a sudden and significant increase in P ura occurs in the at-rest profile.Higher values of TC correlate with positive SUI treatment effects.

In turn, differences in the readings between individual channels in patient G010 (who had undergone SUI surgical treatment with good efficacy and full continence) - negative urethral closure pressure during provocation tests in channel P1 with a lower TC (42%), and no negative pressures in the remaining channels, P2 channel is presented for comparison, and higher TC (59%) in P2 may indicate a high adaptive potential of the functionality of the urethral continence mechanisms and hence the requirement for continence is not the total efficiency of these mechanisms of the whole urethra circumference. The fulfillment of this requirement is illustrated here by a mid-urethral sling which results in continence function in the side area of the urethra.

A low T.C. (transmission coefficient) seems to be characteristic among patients with complaints of SUI, whereas in healthy patients there is a significant variation in the value of this coefficient [30-267%] A potential subject of further studies requiring long-term observation would be to use the coefficient as a predictor of future incontinence in patients with low values of this parameter.

A low resting pressure was found in patient G 011 who had undergone numerous urogynecological procedures with persistent incontinence. In fact, it was the lowest in the studied urethral vector volume and also exhibited significant differences in pressure distribution between individual channels. By shifting the location of the maximum intraurethral pressure in the channels P2 and P3 towards the distal part of the urethra into the region in which the remaining channels register the ending of the resting profile, most likely is a result of the filling material implanted in this region however it does not fulfill its function.

In the control group of patients without urinary incontinence, a significant variation in pressure distribution was found at each radially localized point of measurement. Differences were also found in the functional length depending on the orientation of the sensor - it is not known whether this has an impact on the frequency or severity of complaints. There were also significant differences in transmission coefficient values. A correlation was noticed between the initial intraurethral pressures in the static profile and the amount of pressure generated during provocation tests. This relationship, as well as its effect on the occurrence and type of symptoms, and the causes of increased static pressures in the urethra, requires further investigation. The next parameter to be taken into consideration is L_pmax: (*Length at maximum pressure,* in other words the distance in mm between the maximum pressure point and the start of the high pressure zone) it seems that in patients with stress urinary incontinence there is a tendency for this point to be shifted and the value of this parameter increases.

5. Conclusions

Three-Dimensional profilometry likely results in the elimination of testing errors due to changes in the position of the catheter in the measurement channel. By using three-dimensional profilometry, the dimensional distribution of pressure in the urethra can also be comprehensively assessed during a stress test. Three-dimensional pressure distribution images can be obtained using dedicated software, and these images do not require complicated analysis. The results of the preliminary studies show a significant variation in urethral parameters in the group of patients without symptoms. Thus In the group of patients with incontinence of various types tendencies of certain characteristic changes can be observed.

Establishing norms and characteristic values for different types of problems requires research on a larger groups of patients. Trying to evaluate risk factors for urinary incontinence using specific parameters in healthy patients requires long-term observation. Examinations performed on patients who have already undergone urogynecological procedures could potentially lead to finding unknown risk factors, or uncovering factors which could determine the success of operations used to treat incontinence. It seems that this method with probably its high reproducibility allows for the collection of very accurate data on pressure distribution in the urethra. Dimensional images obtained using this method may lead to the rapid assessment of urethral dysfunction and also pinpoint its location which may be useful in SUI surgery. It should be pointed out that this method will potentially be useful in the diagnosis of the urethra, especially in the diagnosis of stress urinary incontinence and complicated cases of urinary incontinence. It can also be useful in the evaluation of urethral disorders in patients who have previously undergone procedures in the genital and lower urinary tracts, such as removal of an obstacle blocking the flow of urine in the urethra. Both the assessment of the repeatability of the study and the suitability for the assessment in specific clinical cases require further research on a larger groups of patients. These further trials are already performed in our department, together with 3D profilometry repeatability study.

Author Contributions: Conceptualization, Hanna Szweda; methodology, Wioletta Katarzyna Szepieniec, Paweł Szymanowski.; validation, Hanna Szweda, Paweł Szymanowski.; formal analysis, Paweł Szymanowski.; investigation, Wioletta Katarzyna Szepieniec, Hanna Szweda.; resources, Wioletta Katarzyna Szepieniec, Hanna Szweda; data curation, Maksym Wróblewski.; writing—original draft preparation, Wioletta Katarzyna Szepieniec.; writing—review and editing Hanna Szweda.; visualization, Maksym Wróblewski.; supervision, Paweł Szymanowski.; All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: Technical support was assured by 'International Service' M.Wróblewski, Warsaw, Poland

Conflicts of Interest: The authors declare no conflict of interest.

References

[1] Aoki, Y., Brown, H. W., Brubaker, L., Cornu, J. N., Daly, J. O., & Cartwright, R. Urinary incontinence in women. *Nature reviews. Disease primers*, 2017, *3*, 17042. doi: 10.1038/nrdp.2017.42.

[2] www.sciencedaily.com/releases/2018/11/181101085113.htm

[3] Fritel X, Fauconnier A, Levet C, Bénifla JL. Stress urinary incontinence 4 years after the first delivery: a retrospective cohort survey. *Acta Obstet Gynecol Scand*. 2004;83(10):941-945. doi:10.1111/j.0001-6349.2004.00457.x

[4] Lose, G., Griffiths, D., Hosker, G., Kulseng-Hanssen, S., Perucchini, D., Schaefer, W., et al. Standardisation of urethral pressure measurement: Report from the standardisation sub-committee of the International Continence Society. *Neurourol Urodyn*. 2002;21(3):258-260 ** doi: 10.1002/nau.10051.

[5] Kirby AC, Tan-Kim J, Nager CW. Measurement of dynamic urethral pressures with a high-resolution manometry system in continent and incontinent women. *Female Pelvic Med Reconstr Surg*. 2015;21(2):106-110. doi: 10.1097/SPV.0000000000000135.

[6] Haylen, B. T., De Ridder, D., Freeman, R. M., Swift, S. E., Berghmans, B., Lee, J., et al An international urogynecological association (IUGA)/international continence society (ICS) joint report on the terminology for female pelvic floor dysfunction. *Neurourol Urodyn* 29:4–20 (2010) **https://doi.org/10.1002/nau.20798**

[7] Rosier PFWM, Schaefer W, Lose G, Goldman HB, Guralnick M, Eustice S et al. International Continence Society Good Urodynamic Practices and Terms 2016: Urodynamics, uroflowmetry, cystometry, and pressure-flow study. *Neurourol Urodyn*. 2017;36(5):1243-1260 doi: 10.1002/nau.23124.

[8] Holt, P. , Gibbs, C. , Wathes, C., Simultaneous urethral pressure profilometry using a microtip transducer catheter in the bitch: Effects of bitch position and transducer orientation. *Neurourol Urodyna.*1990; 9. 281-296. **https://doi.org/10.1002/nau.1930090306**

[9] Klopper PJ, Haas de D, Dijkhuis T: Computerized experimental multi-channel urethral pressure profilometry. *World J Urol* 1990;8:159-162 ** **doi**: 10.1126/science.291.5502.277

[10] Weber AM. Leak point pressure measurement and stress urinary incontinence. *Curr Womens Health Rep*. 2001;1(1):45-52

[11] Wang AC, Chen MC. A comparison of urethral pressure profilometry using microtip and double-lumen perfusion catheters in women with genuine stress incontinence. *BJOG*. 2002;109(3):322-326.
https://doi.org/10.1111/j.1471-0528.2002.01001.x

[12] Messelink EJ, Dobbe I, Kools C, Dabhoiwala NF Dijkhuizen T, Schneider P et al. Technical Features of the System Used to Perform Multichannel Urethral Pressure Profilometry *Tech Urol Fall* 1997;3(3):158-63,

[13] Nickel RF Simultaneous Diuresis Cysto-Urethrometry and Multi-Channel Urethral Pressure Profilometry in Female Dogs With Refractory Urinary Incontinence *Am J Vet Res* 1997 Jul;58(7):691-6.

[14] Klünder M, Sawodny O,Amend B,Ederer M,Kelp A ,Sievert KD
et al. Signal processing in urodynamics: towards high definition urethral pressure profilometry, *BioMed Eng OnLine* (2016) 15:31

[15] Messelink EJ, Dabhoiwala NF, Vrij V, Dijkhuizen T, Schneider P, Dobbe I, et al Multichannel urethral pressure profiles: reproducibility and three-dimensional representation. *J Endourol*. 1997;11(3):211-214.