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# Experimental Study of the Pressure-Volume and Pressure-Time Relations in the Completely Obstructed Pelvis of the Porcine Kidney

## Part 2: The Relation Between Actual Hydrostatic Pressure, Intrapelvic Volume and Time

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**Summary.** In a series of experiments with pigs the completely obstructed renal pelvis was infused with Ringer's lactate at a constant rate of 2 ml/min. At various pressure levels (lower than 50 mm Hg) the relations pressure vs infused volume and pressure vs actual intrapelvic volume and the effects on the intrapelvic pressure of rapid total or partial extraction of the actual volume were measured. At pressure levels lower than 15–20 mm Hg the P-V relation is exponential; at pressure levels between approximately 20 to 50 mm Hg this relation is linear. In the pressure range from 20 to 50 mm Hg the pressure decays, at a constant or increasing volume, asymptotically to a certain stabilisation value when the infusion is stopped. The relation between stabilised pressure and intrapelvic volume is linear.

**Key words:** Research, Ureteral obstruction, Porcine upper urinary tract, Pressure-volume-time relations.

## Introduction

The mathematical description of the pressure curve that is recorded when the pelvis is infused at a constant rate of 2 ml/min is based upon the assumption that the infused volume at any moment is equal to the actual pelvic volume.

Various mechanisms – tubular reflux and absorption, peripelvic extravasation, diuretic activity – may cause pelvic volume changes which invalidate the assumption. Therefore, a series of experiments was performed to study the relation between infused volume and actual pelvic volume and to study the effects of rapid total or partial extraction of pelvic contents on peak and stabilised pressure.

## Methods

The experimental setup, the theory of P, V, t relations and the general description of methods and materials have been presented in Part 1 of this series.

1. In 9 experiments the pelvis was infused (2 ml/min) until peak pressure values ($P_p$) of 15, 20, 30, 40 and 50 mm Hg were reached. After the desired pressure was reached the infusion was stopped and the pelvic content was rapidly extracted and measured ($V_{out}$) immediately. The infused volume ($V_{in}$) could be accurately calculated from the pressure registration of the recorder. For each of the $P_p$ levels the procedure was repeated at least twice and mean values of $V_{in}$ and $V_{out}$ were calculated. The difference between these mean values were calculated and expressed as a percentage difference (%diff) of $V_{in}$ whereafter mean values and standard deviations were calculated for the % diff. values of each of the $5P_p$ levels.

2. In 8 experiments the pelvis was repeatedly infused until varying $P_p$ values between 15 and 30 mm Hg were recorded. When the desired $P_p$ value was reached the pelvic content was immediately and rapidly extracted and the mean $V_{out}$ value was calculated. Then the pelvis was infused until the same pressure was recorded after which only a fraction of the calculated $V_{out}$ was extracted. The concommitant decrease of intrapelvic pressure was recorded, whereupon the infusion was started again until the original $P_p$ value was measured. Then a larger fraction was extracted. In this way increasing volume fractions were extracted until the fraction approximated the mean $V_{out}$ value. The same procedure was then started at a higher $P_p$ level. By subtracting the volume value of each fraction from the mean $V_{out}$ value an estimation was made of the residing value ($V_r$) of the pelvic volume. For each experiment the estimated residing volumes and the mean $V_{out}$ values were plotted in X-Y scatter diagrams against the corresponding pressure values. Seventeen X-Y distributions were thus obtained with which regression analysis was done.

3. In 16 experiments the pelvis was repeatedly infused until $P_p$ values varying from 15–50 mm Hg were measured. When a particular pressure value was reached the infusion was stopped and the pelvic content was rapidly and totally extracted. The concommitant decrease of pressure was measured and the values of $V_{out}$ were plotted in scatter diagrams against the corresponding pressure decrease. Regression and correlation analysis was done with each of the 16 distributions.

4. In 13 experiments the pelvis was repeatedly infused until peak pressure values of 15, 20, 30, 40 mm Hg were recorded. When a required pressure value was reached the infusion was stopped, the first time the volume was extracted immediately, the second time the peak pressure was allowed to decrease to its stable value ($P_s$) before the pelvic content was extracted. The measurements were repeated at least twice for each of the pressure values. Mean values

Table 1. The relation between $V_{in}$ and $V_{out}$ at $P_p$ levels 15–50 mm Hg. n = 9; %diff = 100 · ($V_{out}$ − $V_{in}$)/$V_{in}$

| $P_p$ | Range %diff | Mean %diff | S.D. %diff |
|---|---|---|---|
| 15 | 3–42 | 18 | 15 |
| 20 | 9–44 | 28 | 12 |
| 30 | 10–50 | 27 | 13 |
| 40 | 11–46 | 23 | 10 |
| 50 | 7–43 | 25 | 12 |

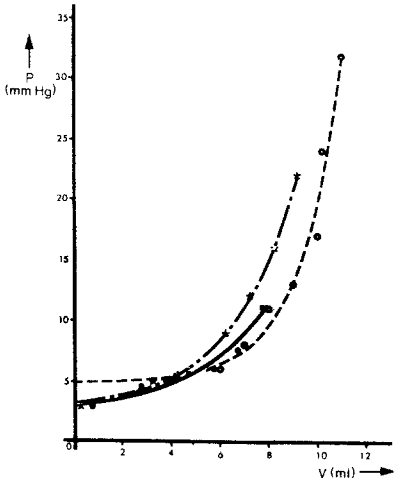


Fig. 1. The relation between $P_p$ and $V_r$ (exp #1 from Table 2)

and standard deviations were calculated for the pressure decreases that had occurred after stabilisation.

5. In 5 experiments the infused volume necessary to reach a particular $P_p$ and corresponding $P_s$ value was calculated from the registrations of the recorder and mean values of $V_{in}$ and $V_{out}$ were calculated for each of the $P_p$ and $P_s$ levels examined. Mean values and standard deviations were calculated for the differences between $V_{in}$ and $V_{out}$ and expressed as percentage difference to $V_{in}$ for each of the examined pressure levels.

6. In 4 experiments the procedure described under 5 was carried out but the measurements were done simultaneously on both sides. For each experiment the values of $V_{in}$ were plotted in an X-Y scatter diagram against the corresponding values of $P_p$ and the recorded values of $P_s$ were plotted against measured values of $V_{out}$.

For the $P_p - V_{in}$ and the $P_s - V_{out}$ distributions regression and correlation analysis was carried out.

## Results

Table 1 shows the results of the 9 experiments in which the infused volumes ($V_{in}$) were compared to the volumes obtained by rapid extraction of the pelvic content. These results show that $V_{out}$ was always larger than $V_{in}$ and for this reason $V_{out}$ values were used in the other experiments.

Figure 1 shows 3 of the 17 scatter diagrams of $V_R - P_p$ values obtained in 8 experiments in which the pelvic volume was alternatively totally or partially extracted at $P_p$ levels between 15 and 30 mm Hg. Table 2 shows the regression equations calculated for each of the 17 distributions. These results show that under these experimental conditions hy-

Table 2. Exponential regression of the P-V relation for $P_p$ < = 30 mm Hg

| # | $P_p$ | exponential regression | # | $P_p$ | exponential regression |
|---|---|---|---|---|---|
| | 15 | $P = 0.8\ e^{0.3V} + 2.1$ | | 17 | $P = 1.2\ e^{1.0V} + 3.0$ |
| 1 | 22 | $P = 0.7\ e^{0.4V} + 2.3$ | 5 | 22 | $P = 0.7\ e^{0.9V} + 3.8$ |
| | 32 | $P = 0.04\ e^{0.6V} + 4.9$ | | 31 | $P = 3.3\ e^{0.7V} + 1.4$ |
| | 18 | $P = 0.1\ e^{1.5V} + 8.6$ | 6 | 32 | $P = 3.6\ e^{0.8V} + 5.7$ |
| 2 | 23 | $P = 0.1\ e^{1.1V} + 9.5$ | | 15 | $P = 2.9\ e^{0.5} + 3.0$ |
| | 33 | $P = 0.4\ e^{0.8V} + 8.3$ | 7 | 21 | $P = 28\ e^{0.1V} - 22$ |
| 3 | 32 | $P = 0.3\ e^{0.6V} + 4.2$ | | 30 | $P = 1.8\ e^{0.6V} + 3.7$ |
| 4 | 32 | $P = 3.1\ e^{0.6} - 1.0$ | 8 | 20 | $P = 166\ e^{0.03V} - 155$ |
| | | | | 30 | $P = 4.2\ e^{0.7V} + 7.4$ |

Table 3. Linear regression of the P-V relation for $P_p$ > = 20 mm Hg

| # | *N* | Linear regression | *R* | # | *N* | Linear regression | *R* |
|---|---|---|---|---|---|---|---|
| 1 | 20 | P = −21 + 5.0 V | 0.92 | 9 | 30 | P = −16.3 + 4.7 V | 0.95 |
| 2 | 36 | P = −4.8 + 4.1 V | 0.96 | 10 | 20 | P = −22 + 14.1 V | 0.96 |
| 3 | 18 | P = −6.4 + 10.0 V | 0.94 | 11 | 34 | P = −8 + 14.0 V | 0.94 |
| 4 | 16 | P = −35 + 6.6 V | 0.95 | 12 | 32 | P = −17 + 9,9 V | 0.97 |
| 5 | 28 | P = −24 + 6.2 V | 0.97 | 13 | 32 | P = −0.2 + 6.8 V | 0.96 |
| 6 | 24 | P = −68 + 11.0 V | 0.96 | 14 | 22 | P = −17 + 12.2 V | 0.94 |
| 7 | 56 | P = −3.8 + 3.6 V | 0.95 | 15 | 30 | P = − 9 + 9.0 V | 0.98 |
| 8 | 30 | P = −17.2 + 5.2 V | 0.98 | 16 | 28 | P = −24 + 10.9 V | 0.96 |

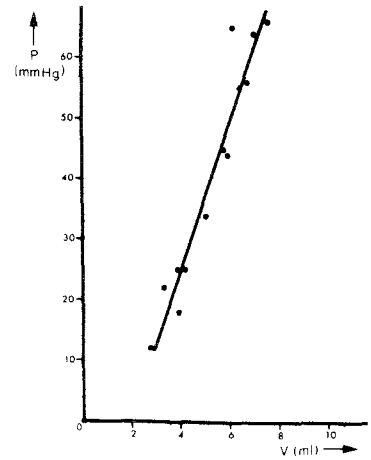


Fig. 2. The relation $P_p - V_{out}$ at $P_p$ = > 30 mm Hg

Table 4. The relation between $P_p$ and $P_s$. %diff = 100 · $(P_p - P_s)/P_p$

| $P_p$ | $N$ | Mean %diff | S.D. %diff |
|---|---|---|---|
| 15 | 8 | 0 | 0 |
| 20 | 13 | 1 | 2.2 |
| 30 | 13 | 10 | 6.4 |
| 40 | 13 | 18 | 4.9 |
| 50 | 10 | 21 | 5.5 |

drostatic intrapelvic pressure changes in an exponential manner with volume when the pressure is lower than 20 mm Hg.

Figure 2 shows one of the 16 scatter diagrams in which the rapidly extracted total pelvic volume ($V_{out}$) was plotted against the corresponding pressure decreases at $P_p$ values varying from 15–50 mm Hg. Table 3 shows the regression equations and coefficients for linear regression that were calculated for each of the 16 scatter diagrams. These results show that there was a linear relation between intrapelvic volume and pressure; once intrapelvic pressure was higher than approximately 20 mm Hg.

Table 4 shows the mean values plus SD of the pressure decreases that occurred in 13 experiments in which peak pressure was allowed to decrease to a stable value at 5 $P_p$ levels varying from 15–50 mm Hg. The results show that peak pressure decreases progressively as the $P_p$ pressure value was higher and varied from approximately 1 percent at the 20 mm Hg level, to 20 percent at 50 mm Hg level.

Table 5 shows the results of 5 experiments in which the infused and extracted volumes at 5 $P_p$ levels were compared to corresponding volume values after the peak pressure had decreased to a stabilised value. The results show that on all 5 pressure levels the decrease of pressure during stabilisation occurred at constant or increasing volume.

Figure 3 shows one of the 4 scatter diagrams in which $V_{in}$ values were plotted against corresponding $P_p$ values and the $P_s$ values against $V_{out}$ values obtained in 2 experi-

Table 5. The relation between $P_p$, $P_s$ and $V_{in}$, $V_{out}$. %diff = 100 · $(V_{out} - V_{in})/V_{in}$

| $P_p$ | $N$ | Range %diff | Mean %diff $P_p$ | S.D. %diff | Range %diff | Mean %diff $P_s$ | S.D. %diff |
|---|---|---|---|---|---|---|---|
| 15 | 2 | 5–42 | 24 | 26 | 44–74 | 59 | 21 |
| 20 | 5 | −2–36 | 19 | 17 | 17–48 | 32 | 12 |
| 30 | 5 | 11–28 | 18 | 8 | 9–26 | 19 | 7 |
| 40 | 5 | 18–29 | 22 | 6 | 9–32 | 23 | 9 |
| 50 | 5 | 18–28 | 22 | 5 | 4–41 | 23 | 13 |

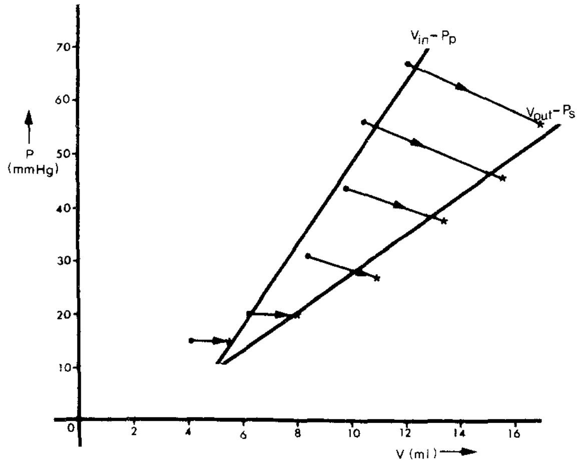


Table 6. The relation $P_s - V_{out}$ (simultaneous measurements on both sides)

| # | $N$ | Linear regression | $R$ |
|---|---|---|---|
| 1 | 20 | P = 0.8 + 1.5 V | 0.96 |
| 2 | 20 | P = 2.1 + 1.9 V | 0.99 |
| 3 | 22 | P = 2.4 + 2.8 V | 0.98 |
| 4 | 22 | P = 6.8 + 3.1 V | 0.94 |

◀ Fig. 3. The relation $P_p - V_{in}$ and $P_s - V_{out}$. (Simultaneous measurements on both sides) ments in which simultaneous measurements on both sides were done.

Table 6 shows the calculated regression equations and correlation coefficients for linear regression that were calculated for the four $P_s - V_{out}$ distributions. These results illustrate that during the stabilisation phase the volume increased with pressure decreasing to a stable value. They show that there was a marked linear relation between intrapelvic stabilised pressure and volume.

## Conclusions

When the completely obstructed porcine pelvi-calyceal system under experimental conditions is infused at constant rates (2 ml/min) intraluminar pressure increases initially in an exponentional manner with volume until pressure values of approximately 20 mm Hg are recorded. At further increase of the pelvic volume there is a marked linear relation between volume and pressure until pressure values of over 50 mm Hg are recorded. When the infusion is ceased, the pelvic pressure stabilises at a level which is relatively lower as the peak pressure is higher. The decrease of pressure during stabilisation occurs at constant or increasing pelvic volume and a marked linear relation between pressure and volume is maintained during stabilisation. Apparently there occurs stress relaxation of the pelvi-calyceal system which has been found to be stable at pressure levels lower than 50 mm Hg. At pressure levels higher than 50 mm Hg however, continuous infusion may lead to blow out and extravasation of intrapelvic fluid. The phenomenon of stability and blow out in the totally obstructed porcine pelvi-calyceal system will be subject of further study.

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