World Journal of Urology (2019) 37:133–142
https://doi.org/10.1007/s00345-018-2379-3

INVITED REVIEW

Pressure matters 2: intrarenal pressure ranges during upper-tract endourological procedures

Theodoros Tokas[1] · Andreas Skolarikos[2] · Thomas R. W. Herrmann[3] · Udo Nagele[1] · Training and Research in Urological Surgery and Technology (T.R.U.S.T.)-Group

Received: 1 May 2018 / Accepted: 12 June 2018 / Published online: 18 June 2018

Abstract

Purpose To perform a review on the latest evidence related to intrarenal pressures (IRPs) generated during upper-tract endourology, and present different tools to maintain decreased values, to decrease complication rates.

Methods A literature search was performed using PubMed, restricted to original English-written articles, including animal, artificial model and human studies. Different keywords were: percutaneous nephrolithotomy, PCNL, ureteroscopy, URS, RIRS, irrigation flow, irrigation pressure, intrarenal pressure, intrapelvic pressure and renal-pelvic pressure.

Results IRPs reported during retrograde intrarenal surgery (RIRS), PCNL, miniPCNL, and microPCNL range 40.8–199.35, 3–40.8, 10–45 and 15.37–41.21 cm H_2O, respectively. By utilizing ureteral access sheaths (UASs) IRPs usually remain lower than 30 cm H_2O at an irrigation pressure (IP) of $\leq$ 100 cm H_2O but could increase to $>$ 40 cm H_2O at an IP of 200 cm H_2O. By utilizing the minimally invasive PCNL system, IRPs remain low at 20 cm H_2O even at high IPs. Utilizing endoluminal isoproterenol during RIRS, could reduce IRP increases with a rate of 27–107%, and maintain low IRPs values, usually below 50 cm H_2O.

Conclusions Increased IRP values have been reported during RIRS and UASs constitute the most efficient tool for decreasing them. IRPs during mini-PCNL can be decreased utilizing the vacuum-cleaner and purging effects but might remain uncontrolled during micro- and ultra-mini PCNL. Intraluminal pharmacological treatment could play a role in IRP decrease, with isoproterenol being the most studied agent.

Keywords Percutaneous nephrolithotomy · PCNL · Ureteroscopy · URS · RIRS · Irrigation flow · Irrigation pressure · Intrarenal pressure · Intrapelvic pressure · Renal-pelvic pressure

Introduction

Endourological upper-tract treatment constitutes a main field in everyday urology. Retrograde intrarenal surgery (RIRS) and percutaneous nephrolithotomy (PCNL) constitute the main means of active renal stone treatment and are characterized by a huge variety of new techniques and instrumentation. To achieve better visibility during a procedure, irrigation flow (IF) and irrigation pressures (IPs) have to be increased. Nevertheless, consequent intraoperative increments in intrarenal pressures (IRPs) are able to deteriorate any procedure and IRPs lower than 30 cm H_2O should be maintained to avoid complications. Yet, only a few endourologists are aware of normal and pathological IRP values, as well as usual IRP ranges during different procedures.

✉ Theodoros Tokas
ttokas@yahoo.com

[1] Department of Urology and Andrology, General Hospital Hall in Tirol, Milser Str. 10, 6060 Hall in Tirol, Austria

[2] Second Department of Urology, Sismanoglio General Hospital, Athens Medical School, Athens, Greece

[3] Department of Urology, Kantonspital Frauenfeld, Spital Thurgau AG, Frauenfeld, Switzerland

Materials and methods

Evidence acquisition

A review of the literature was performed using PubMed. Original works restricted to the English language were identified. We included articles discussing IRP, IP, and IF in endourology. All experimental and observational studies

were judged as eligible, including but not restricted to controlled clinical trials, case series, case–control and cohort studies. Reviews, comments and editorials were excluded. The literature search was conducted by the first author using the keywords, percutaneous nephrolithotomy OR PCNL, ureteroscopy, OR URS, OR RIRS, and then restricted with the keywords (AND) irrigation flow, OR irrigation pressure OR intrarenal pressure OR intrapelvic pressure OR renal-pelvic pressure. This search identified 552 records (Fig. 1). After excluding duplicate references, 511 unique references were reviewed by title or abstract. A list of articles judged to be highly relevant by the junior (T.T.) and senior (U.N.) authors was distributed to the coauthors, to reach a final consensus on the articles included and the structure of the review. Eligible studies known to the authors but not identified by the search were also evaluated for inclusion,

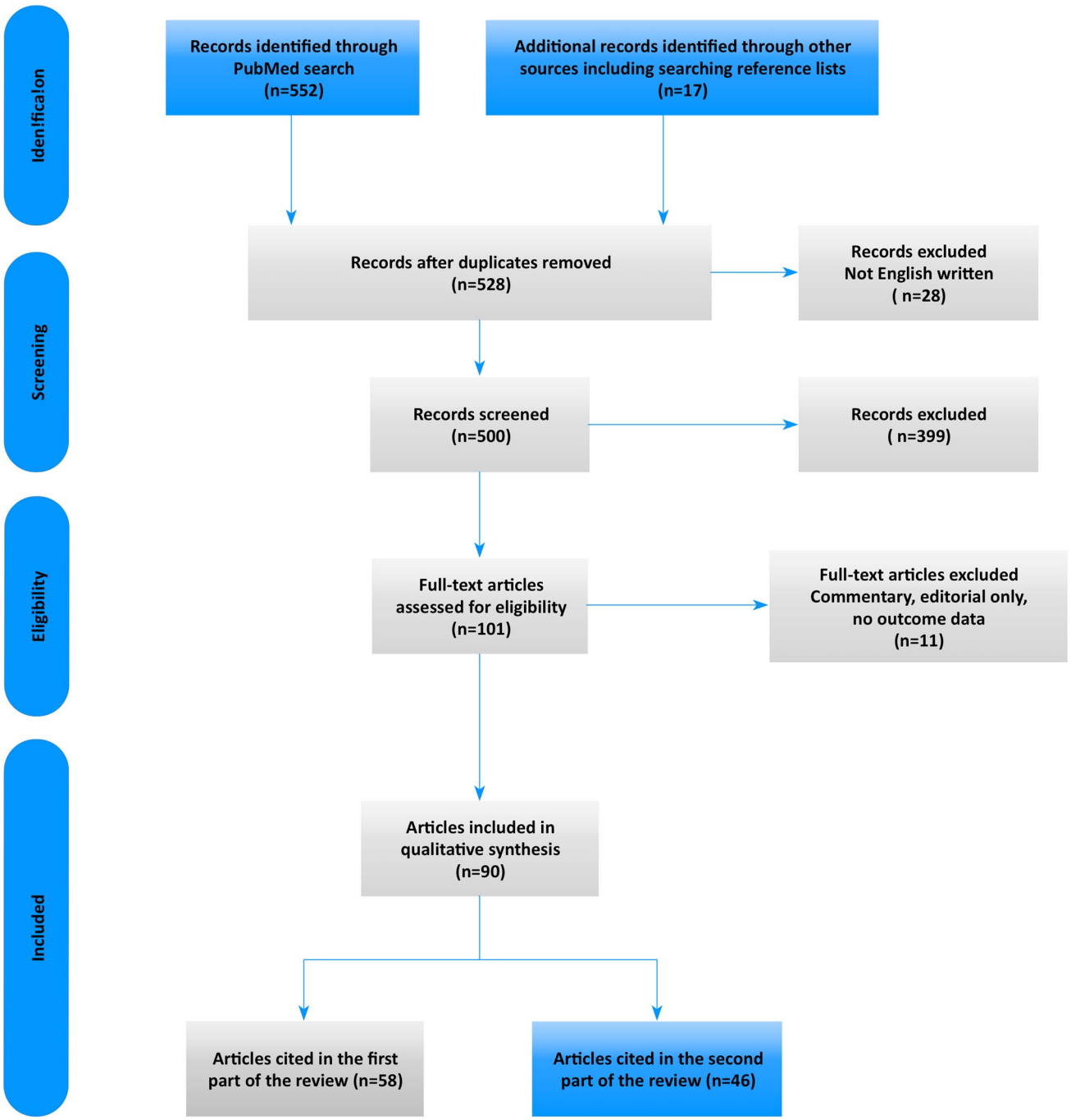

Fig. 1 Flowchart of the literature reasearch

adding an additional 17 unique records. A total of 90 unique references (experimental studies, controlled clinical trials, case series, case–control and cohort studies) were included in the qualitative synthesis. Due to study heterogeneity and the nonstandardized quality appraisal, a narrative synthesis was performed. The limitations of using a single database for review are taken into account [1]. Moreover, outcomes may be limited by study heterogeneity and selection bias. IRPs are measured in cm H_2O, mm Hg, or mbar. In this work, all pressures were converted to cm H_2O (1 cm $H_2O = 0.73$ mm Hg = 0.97 mbar) which is the most common IRP unit in the international literature. Due to the journal word and reference restrictions, the review was divided into two works. This second part deals with reported IRPs, during different upper-tract endourological procedures and presents possible ways to maintain low pressures even by increasing IF.

Outcomes

IRPs during RIRS (Table 1)

Nine studies [2–10] have been identified, five [2, 6–9] human, one [4] in vitro human cadaveric, one [2] in vitro mini-pig, and one [10] in vivo porcine study. Five studies [2, 3, 8–10] utilized semi-rigid ureteroscopes, four [4–7] flexible ureteroscopes, and one [3] study utilized both. The irrigation pressures reported are 68–272 cm H_2O [2–4, 9]. The FRs are reported only in three studies and range from 8 to 27 mL/min [4, 6, 7]. The irrigation is usually based on gravity and also includes powerful manual irrigation [3, 5]. The IRPs reported range 8.27–199.35 cm H_2O depending on the IP used. The maximal IRPs measured during powerful manual irrigation reach 598.4 cm H_2O [2, 3].

RIRS devices that influence IRPs

*Ureteral access sheaths (UASs) (*Table 2*)* We have identified five studies [4, 5, 11–13] assessing IRPs during flexible ureteroscopy (fURS). Of them, only one [5] is an in vivo human, one [4] being an in vitro cadaveric, one [11] ex vivo porcine, and two [12, 13] in vitro artificial model studies. Multiple flexible ureteroscopes with variable calibers have been tested (6.9–8.5 mm). The UAS sizes tested were 9.5/11.5 F [13], 10/12 F [4, 11–13], 11/13 F [13], 12/14 F [4, 5, 12, 13] and 14/16 F [4, 12]. IPs were set up to 60 cm H_2O in one study [13], 100 cm H_2O in two studies [11, 12], and 200 cm H_2O in two studies [4, 12], as one work did not report IPs [5]. The range of achieved FRs, according to IP, ureteroscope and UAS size, was 2.83–50 mL/min [4, 11–13]. At IPs of 60–100 cm H_2O, IRPs were 33.8–46.68, 13.4–57.00, 4.08–29.00, 2.72–< 20.00, and < 20.00 cm H_2O for UASs of 9.5/11.5 F, 10/12 F, 11/13 F, 12/14 F, and 14/16 F, respectively. At IPs of 200 cm H_2O, reported IRPs showed great variations, as in one study [4] IRPs ranged 14.5–29 cm H_2O, while in another [12] IRPs ranged 40–100-cm H_2O not taking into account the UAS caliber. An important conclusion is that at an IP of ≤ 100 cm H_2O, IRPs remain lower than 30 cm H_2O if a UAS bigger than 10/12 F is utilized. An IP of 200 cm H_2O may offer high irrigation flows but could result in IRPs > 40 cm H_2O. There are no significant differences between flow and pressure of the 12/14F and the 14/16F UAS. Most importantly, the compatibility between the ureteroscopes and UASs should be anticipated and considered during fURS [11].

Other devices The automated infusion/pressure control devices include pre-setting the desired IRP and altering the IP with an automated irrigation/suction pump system to maintain the desired IRP [14–17]. Perfusion flow is usually set at 50–150 mL/min, IRP warning value at 27.2 cm H_2O, and maximum (limit) value at 40.8 cm H_2O [17]. Such devices can monitor additional vital parameters like body temperature [18].

Pedal irrigation [19] or roller pump devices [3] are able to deliver irrigant boluses and continuous high-flow through the ureteroscope. By utilizing IPs of 100–272 cm H_2O, high IRPs ranging 92–149.6 cm H_2O have been recorded [3, 19]. At the same time, by manual 60 mL syringe irrigation, IRPs reach 156.4 cm H_2O by gentle, and 469.2–557.6 cm H_2O by powerful irrigation [3].

Various devices have been designed to prevent retrograde stone migration by occluding the lumen of the ureter proximal to the stone. An additional benefit of these devices may be a decrease in IRP from retardation of irrigant flow into the renal pelvis. Utilizing coil or multifold film antirepulsion devices, presented IRPs ranging 7.62–19.04 cm H_2O and 7.62–19.04 cm H_2O, respectively, even at high IPs of 408 cm H_2O [20].

By utilizing instruments with combined inflow and outflow channel, problems concerning good vision on the one hand and high IRP on the other hand can occur. The continuous-flow semi-rigid ureteroscope can provide a 100 times higher flow capacity while simultaneously preserving IRPs of 15 cm H_2O and < 20 cm H_2O at an irrigation solution level of 50 cm and 100 cm, respectively [21].

Finally, the use of a micro- semi-rigid ureteroscope (4.85 Fr) seems to achieve IRPs lower than 40.8 cm H_2O at 90% of the cases [10].

IRPs during PCNL (Table 3)

Eleven studies [22–32] have been identified. Five of them [25–28, 31] were in vivo human studies, one [24] was an in vitro human kidney model, one [30] an ex vivo human cadaveric model, two [23, 29] were in vitro chamber or cast-based artificial models, one [22] included an in vivo

Table 1 IRPs during RIRS

Study	Year	Experiment	Instruments	Pressure measurement	IP in cm H_2O	FR	Pressures measured	Irrigation	Concomitant obstruction	Mean pressures (range) in cm H_2O	Maximum pressures in cm H_2O
Wilson et al. [3]	1990	In vivo, human	sURS, fURS	Antegradely (tip)	100	NA	IRP	Gravity + manual	No	(40.8–61.2)	598.4 (with powerful manual irrigation)
Schwalb et al. [2]	1993	In vitro, minipig kidneys	sURS	Antegradely (tip)	< 122.4 > 204		IRP			NA	597.04
Rehman et al. [4]	2003	In vitro, cadaveric kidneys	fURS	Antegradely (tip)	100 200	47–54 mL/3 min 79–81 mL/3 min	IRP	Gravity	NA	30 51.5–58.9	59.92
Auge et al. [5]	2004	In vivo, human	fURS	Antegradely (tip)	NA	NA	DU MU PrU IRP	Gravity + manual	No	81.6 89.22 107.71 128.38	NA
Jung et al. [6]	2008	In vivo, human	fURS	Retrogradely (tip)	NA	8 mL/min	IRP	Gravity	NA	44.88	432.48
Jung et al. [7]	2008	In vivo, human	fURS	Retrogradely (tip)	NA	8 mL/min	IRP	Gravity	NA	63.92	490.96
Cai et al. [8]	2012	In vivo, human	sURS	Retrogradely (outflow)	NA	NA	Ureter	NA	Acute Chronic No	101.32 (29.92–244.8) 44.2 (12.24–72.08) 13.87 (10.88–17.68)	NA
Shao et al. [9]	2012	In vivo, human	sURS	Antegradely (tip)	68 136 272		IRP			46.06 ± 6.85 99.07 ± 14.62 166.27 ± 33.08	NA
Caballero-Romeu et al. [10]	2018	In vivo, porcine	sURS m-URS	Antegradely (tip)	NA	NA	IRP	Gravity	No	8.27–28.07 6.90–19.18	40.8 in 35% 40.8 in 10%

sURS semirigid ureteroscopy *fURS* flexible ureteroscopy *m-sURS* micro-semirigid ureteroscopy *PCN* percutaneous nephrostomy *DU* distal ureter *MU* middle ureter *PrU* proximal ureter *NA* not available

Table 2 IRPs during RIRS with UAS

Study	Year	Experiment	FURS Scope caliber in F	UAS caliber in F	Measurement	IP (cm H_2O)	FR (mL/min)	Mean IRPs in cm H_2O
Rehman et al. [4]	2003	In vitro, cadaveric kidneys	7.5	10/12 12/14 14/16	Antegradely (PCN)	200	36.3–50	22.3–29.0 16.8–19.8 14.5–19.5
Monga et al. [11]	2004	Ex vivo, porcine kidneys	8.5 7.5	10/12	Retrogradely (tip)	100	< 15	> 54.4 21.76–< 40.8
Auge et al. [5]	2004	In vivo, human	6.9/8.4	12/14	Antegradely (PCN)	NA	NA	20.4–55.22
Ng et al. [12]	2010	In vitro anatomic model	7.5	10/12 12/14 14/16	Antegradely (connection)	100 200	4.6–28 40–50	29–57 < 20 < 20 40–100
Emre Sener et al. [13]	2016	In vitro artificial model	Multiple scopes 7.5–8.5	9.5/11.5 10/12 11/13 12/14	Retrogradely (tip)	60	2.83–17.13	33.8–46.68 13.4–33.99 4.08–29.00 2.72–15.86

fURS flexible ureteroscopy *PCN* percutaneous nephrostomy *NA* not available *IP* irrigation pressure *FR* flow rate

human as well as in vitro pork kidney models, and one [32] an in vivo porcine model. Six groups [22–25, 30, 31] utilized standard PCNL, and two [26, 27] miniPCNL (mPCNL). Finally, one study [29] compared IRPs during mPCNL, one [28] compared IRPs during microPCNL with IRPs during standard PCNL, and two compared IRPs during standard PCNL with IRPs during flexible nephroscopy [31, 32]. The IPs ranged 25–130 cm H_2O in seven [22–25, 28, 29, 31] and 200–340 cm H_2O in three studies [26, 27, 32]. In one work the IPs ranged 68–408 cm H_2O [30]. The FRs were calculated in three studies [23, 26, 27], and ranged 0–400 mL/min. The IRPs ranged 3–41.21 cm H_2O in seven PCNL studies [22–24, 28, 30–32] with sheaths ranging 26–34 F, and 13–50 cm H_2O in two PCNL papers utilizing sheaths of 26, and 22 F [24, 29]. In one PCNL study, IRPs were higher than 40.8 cm H_2O only in 24%, and in another, in 35% of the cases [25, 31]. On the other hand, during mPCNL, the IRPs measured ranged < 10–45 cm H_2O with sheath caliber ranging 21–14 F [26, 27, 29, 32]. Finally, IRPs during microPCNL utilizing a 4.8 F micro-shaft ranged 15.37–41.21 cm H_2O [28].

How to maintain sufficient flow and decrease pressure in PCNL

The minimally invasive PCNL (MIP) concept and the vacuum-cleaner effect Due to the big caliber of standard PCNL instruments, IRPs above the level of 40 cm H_2O only rarely complicate the procedure [22–25, 28, 29]. However, by smaller systems, an irrigation backflow via access sheath is not possible. The mismatch between in- and outflow can cause high IRPs. The open sheath designs of the first-generation miniaturized instruments [33] are not sufficient for pressure control, because of the unfavorable ratio of the small inner diameter of the sheath and relatively larger nephroscope diameter, which is necessary for scope stability.

The minimally invasive PCNL (MIP) concept first utilized a 18 F nephroscope sheath with an open proximal end in a cadaveric pork model [33]. The sheath is designed to maintain reduced IRPs whatever the irrigation pressure. The smallest instrument in PCNL with regular backflow, through an access sheath of 11/12 F, is the MIP S (Karl Storz, Germany) [34]. Closing of the control sheath results in an increase in the IRP to a maximum of 136 cm H_2O. Using the sheath with a constant output flow, the maximal IRP remains low at 20 cm H_2O, even when the inflow pressure reaches 125 cm H_2O [33]. The *vacuum-cleaner effect* appears when, in front of the distal end of a round-shaped nephroscope, a slipstream develops, induced by the excursive change of width of the fluid flow on the outlet of the flushing canal. It depends on the relation between the nephroscope and inner sheath diameter. The strongest effect can be observed with a 12 F nephroscope and an inner sheath diameter of 15 F [34].

Ureteral sheaths and ureteral catheters The concept of a retrograde ureteral catheter or UAS placement was introduced during standard PCNL [30]. The authors demonstrated significantly decreased IRPs utilizing a 10/12F or 12/14F UAS (≈ 5–22 cm H_2O), compared with an empty ureter (≈ 11–38 cm H_2O), a ureteral catheter (≈ 15–52 cm H_2O), or an occlusion balloon application (≈ 16–56 cm H_2O). By utilizing a ureteral catheter during mPCNL, the addition of a suction device can assist the washing out of the fluid. A combination of pressure irrigation with a sensor-controlled suction via a modified transurethral 8-Fr mono-J catheter with enlarged draining holes and an increased irrigation flow and reduced IRP could be achieved in a pork

Table 3 IRPs during PCNL

Study	Year	Experiment	Sheath (scope) calibre in F	Pressure measurement	IP (cm H_2O)	FR (mL/min)	Pressures measured	Irrigation	Concomitant obstruction	Mean pressures in cm H_2O	Maximum pressures in cm H_2O
Saltzman et al. [22]	1987	In vitro, porcine	34 (26) No (26)	Antegradely (PCN)	25 50 75 25 50 75	NA	IRP	Gravity	No	5–9 8–12 12–16 13–15 22–23 29–31	29–31
Saltzman et al. [22]	1987	In vivo, human	34 (26) No (26)	Antegradely (PCN)	NA	NA	IRP	Gravity	NA	6.5–8.5 12.5	12.5
Goble et al. [23]	1987	In vitro, model chamber based	26 (23.5)	Antegradely (PCN)	25–75	0 -160	Intracavitary pressures	Gravity	No	16–25	27
Low [24]	1999	In vitro, human nephrectomy	26 (24.5) 30 (24.5)	Retrogradely (tip)	36 52	NA	IRP	Gravity	No	18–36 33–40 3–5	40
Troxel et al. [25]	2002	In vivo, human	30 F (NA)	Retrogradely (tip)	90	NA	IRP	Gravity	NA	< 40.8 in 74% > 40.8 in 26%	80
Landman et al. [30]	2002	Ex vivo, human cadaveric	30 (NA)	Antegradely (PCN)	68 136 204 272 408	NA	IRP	Gravity	NA	15–32	NA
Guohua et al. [26]	2007	In vivo, human	14 (8–9.8) 16 (8–9.8) 18 (8–9.8) double-16 (8–9.8)	Retrogradely (tip)	204–340	250–400	IRP	Gravity	NA	33.8 22.1 15.9 7.9	>/=40.8
Zhong et al. [27]	2008	In vivo, human	14 (8–9.8) 16 (8–9.8) 18 (8–9.8) double-16 (8–9.8)	Retrogradely (tip)	260	300.90	IRP	Gravity	NA	33.4 22.4 15.3 9	>/=40.8 (83.75%)
Tepeler et al. [28]	2014	In vivo, human	4.8 micro-shaft 30 (24)	Retrogradely (tip)	68 90	NA	IRP	Pump Gravity	NA	15.4–41.2 11.8–27.3	51.1 36.4
Mager et al. [29]	2015	In vitro, model based on a watertight cylindrical cast	26 22 21 (12) 16.5 (12) 15 (12)	Antegradely (working channel)	40–130	NA	Intracavitary pressures	Gravity	No	< 20 13–50 < 10 10–20 20–45	NA

Table 3 (continued)

Study	Year	Experiment	Sheath (scope) calibre in F	Pressure measurement	IP (cm H_2O)	FR (mL/min)	Pressures measured	Irrigation	Concomitant obstruction	Mean pressures in cm H_2O	Maximum pressures in cm H_2O
Loftus et al. [32]	2018	In vivo porcine	14/16 (8/9.8) 30 (26)	Retrogradely (tip)	200	NA	IRP	Gravity	No	25.51 18.44	> 40.8 for 116.99 min > 40.8 for 66.07 min
Alsyouf et al. [31]	2018	In vivo, human	30 (26)	Retrogradely (tip)	110	NA	IRP	Gravity	No	41.21	> 40.8 in 35%

PCN percutaneous nephrostomy *NA* not available *FR* flow rate

cadaveric model [35]. The so-called *purging effect* could decrease IRPs by 14% at 102 cm H_2O (19–14.5 cm H_2O) and 28% at 149.6 cm H_2O inflow pressure (37–26.5 cm H_2O).

Pressure/suction connected with the nephroscope Song et al. [36] presented a patented irrigation and clearance system utilized during mPCNL (16 F). Irrigation volume was set at 600–800 mL/min, irrigation pressure was set at 340–408 cm H_2O, and suction pressure at 136–340 cm H_2O. The mean IRP remained 5.58 cm H_2O. Yang et al. [37] presented a mini-PCNL (12F) setting with intelligent monitoring and control of IRPs in a range of − 16.32 to 2.72 cm H_2O.

Local (intraluminal) pharmacological treatment to decrease IRPs (Table 4)

It has been shown that ureteral smooth muscle is relaxed by β_2 and β_3-adrenergic stimulation [38]. However, there are significant species differences in functional β-adrenoceptor subtypes mediating ureteral smooth muscle relaxation, that is mainly β_1-adrenoceptor in rats, β_2-adrenoceptor in rabbits, mainly β_3-adrenoceptor in dogs, and β_2 and β_3-adrenoceptors in humans [39, 40]. The three catecholamines (isoprenaline, noradrenaline and adrenaline) decrease tonic contraction in a concentration-dependent manner. In terms of relaxing potency, the rank order is isoprenaline > adrenaline > noradrenaline. Their perspective of modulating upper urinary tract dynamics during endoscopy could be of potential benefit.

We identified nine studies [6, 7, 41–47] assessing the impact of intraluminal application of different agents in IRP changes. The first porcine study [41] evaluated the impact of verapamil, prostaglandin F2α, phenylephrine and norepinephrine (NE) at different concentrations and with a perfusion rate of 2 mL/min. No agent demonstrated significant IRP variations. The influence of NE alone was researched in three porcine studies [42, 43, 45], in different concentrations (1, 5, 50 and 100 µg/mL) and perfusion rates (2, 4, 6, 8, 10, 15 mL/min). In one study [42], a delayed increase and a decrease in IRP by increasing flow rates and using 5 and 50 microg/mL NE was recorded (< 20.4 cm H_2O). Additionally, a 100 microg/mL NE significantly inhibited and almost eliminated the IRP increase at all perfusion rates compared with saline perfusion (< 13.6 cm H_2O). The next two studies [43, 45] recorded diminished IRP increase at all NE concentrations and at all flow rates, in a dose-dependent manner, as IRPs remained < 16.32 and < 21.76 cm H_2O, respectively. In one study, a significant increase of systolic blood pressure at NE concentrations of 50 and 100 µg/mL was recorded [43].

Five studies [6, 7, 44, 46, 47] assessed the impact of isoproterenol (ISO) administered at various concentrations (10^{-5}, 10^{-4}, 10^{-3}, 10^{-2}, 0.1 and 10 µg/mL) and perfusion rates (2, 4, 5, 8, 10, 15 mL/min). Three of them [44, 46,

Table 4 Local (intraluminal) pharmacological treatment to decrease IRPs

Study	Year	Experiment	Measurement	Substance	Concentration	Perfusion/FR (mL/min)	IRP changes	Systemic effects	Maximum % decrease of IRP increase without systemic effects
Selmy et al. [41]	1994	In vivo pig	Antegradely (PCN)	Verapamil Prostaglandin F2α Phenylephrine Norepinephrine	10^{-6} – 10^{-3} mol/L 2×10^{-5}–2×10^{-1} mg 5, 10, 50, 100 µg/mL 5, 10, 50, 100 µg/mL	2	NS[a]	No	NA
Holst et al. [42]	2003	In vivo pig	Retrogradely (tip)	Norepinephrine	0 5 50 100 µg/mL	2, 4, 6, 8, 10, 15	NS[a] NS[a] S[a] decrease of IRP increase only at 4 mL/min[a] S[a] decrease of IRP increase in all FRs[a]	No	NA
Holst et al. [43]	2005	In vivo pig	Retrogradely (tip)	Norepinephrine	0 5 50 100 µg/mL	2, 4, 6, 8, 10, 15	– S[a] S[a] S[a] S[a]	Yes, increase of systolic BP at concentrations of 50 and 100 µg/mL	NA
Jakobsen et al. [44]	2007	In vivo pig	Retrogradely (tip)	Isoproterenol	10^{-5} µg/mL 10^{-4} 10^{-3} 10^{-2} 0.1 10	2, 4, 5, 8, 10, 15	S[a] S[a] NS[a] S[a] S[a] S[a] at 8 mL/min	Yes, decrease of systolic BP and increase HR at a concentration of 10 µg/mL	64% with concentration of 0.1 µg/mL and FR of 8 mL/min
Mortensen et al. [45]	2008	In vivo pig	Retrogradely (tip)	Norepinephrine	0 1 5 50 100 µg/mL	2, 4, 6, 8, 10, 15	– S[a] S[a] S[a] S[a]	No	NA
Jung et al. [46]	2008	In vivo pig	Retrogradely (tip)	Isoproterenol	0.1 µg/mL	8	S	No	42%
Jung et al. [6]	2008	In vivo human	Retrogradely (tip)	Isoproterenol	0.1 µg/mL	8	S	No	88%
Jung et al. [7]	2008	In vivo human	Retrogradely (tip)	Isoproterenol	0.1 µg/mL	8	S	No	107%
Jakobsen et al. [47]	2010	In vivo pig	Antegradely (PCN)	Isoproterenol	0.1 µg/mL	0, 4, 8, 12,16, 25, 33	S decrease of IRP increase in all FRs[a]	Yes, decrease of HR	27% with FR 4 mL/min

PCN percutaneous nephrostomy, *NS* not significant, *S* Significant

[a]Absolute values not given, only diagrams presented

47] were porcine and two [6, 7] were human ureterorenoscopy studies. The maximal decrease of IRP increase without systemic side effects was recorded at concentrations of 0.1 µg/mL and perfusion rates of 4 or 8 mL/min [44, 47]. In these settings, IRP increase could be reduced with a rate of 27–107%. In terms of absolute values, mean IRPs ranged 44.88–70.72 cm H_2O and 25.84–51.68 cm H_2O for saline and ISO, respectively. A decrease of systolic blood pressure and increase of heart rate was reported at a concentration of 10 µg/mL [44].

Conclusions

During RIRS, extremely high IRP values are reported with powerful manual, in comparison to gravity irrigation or pumps, and ureteral access sheaths constitute the most efficient tool for IRP decrease. IRPs during PCNL remain at low levels and IRPS during mini-PCNL can be significantly decreased with the vacuum-cleaner and purging effects but remain uncontrolled during micro- and ultra-mini PCNL. Intraluminal pharmacological treatment could play a role in IRP decrease, with isoproterenol being the most studied agent, however, more human prospective studies are needed to adopt it in our everyday practice. Current evidence remains heterogeneous and there is a lack of proper designed and executed human studies, making IRPs a neglected predictor of upper-tract endourology complications.

Author contributions TT: Data management, data analysis, manuscript writing. AS: Interpreting data. TRWH: Interpreting data. UN: Protocol/project development and Interpreting data.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Human and animal rights This review does not involve human participants and/or animals.

References

1. Falagas ME, Pitsouni EI, Malietzis GA, Pappas G (2008) Comparison of PubMed, Scopus, Web of Science, and Google Scholar: strengths and weaknesses. FASEB J 22(2):338–342. https://doi.org/10.1096/fj.07-9492LSF
2. Schwalb DM, Eshghi M, Davidian M, Franco I (1993) Morphological and physiological changes in the urinary tract associated with ureteral dilation and ureteropyeloscopy: an experimental study. J Urol 149(6):1576–1585
3. Wilson WT, Preminger GM (1990) Intrarenal pressures generated during flexible deflectable ureterorenoscopy. J Endourol 4(2):135–141. https://doi.org/10.1089/end.1990.4.135
4. Rehman J, Monga M, Landman J, Lee DI, Felfela T, Conradie MC, Srinivas R, Sundaram CP, Clayman RV (2003) Characterization of intrapelvic pressure during ureteropyeloscopy with ureteral access sheaths. Urology 61(4):713–718
5. Auge BK, Pietrow PK, Lallas CD, Raj GV, Santa-Cruz RW, Preminger GM (2004) Ureteral access sheath provides protection against elevated renal pressures during routine flexible ureteroscopic stone manipulation. J Endourol 18(1):33–36. https://doi.org/10.1089/089277904322836631
6. Jung H, Norby B, Frimodt-Moller PC, Osther PJ (2008) Endoluminal isoproterenol irrigation decreases renal pelvic pressure during flexible ureterorenoscopy: a clinical randomized, controlled study. Eur Urol 54(6):1404–1413. https://doi.org/10.1016/j.eururo.2008.03.092
7. Jung HU, Jakobsen JS, Frimodt-Moeller PC, Osther PJ (2008) Irrigation with isoproterenol during ureterorenoscopy causes no systemic side-effects. Scand J Urol Nephrol 42(2):158–163. https://doi.org/10.1080/00365590701570631
8. Cai Y, Li X, Zhu B, Chen R, Ye C, Wang Y, Wang Y, Tao Y, Sun Q, Wen X (2012) A practical pressure measuring method for the upper urinary tract during ureteroscopy. Clin Invest Med 35(5):E322
9. Shao Y, Shen ZJ, Zhu YY, Sun XW, Lu J, Xia SJ (2012) Fluid-electrolyte and renal pelvic pressure changes during ureteroscopic lithotripsy. Minim Invasive Therapy Allied Technol: MITAT 21(4):302–306. https://doi.org/10.3109/13645706.2011.595419
10. Caballero-Romeu JP, Galan-Llopis JA, Soria F, Morcillo-Martin E, Caballero-Perez P, Garcia A, La De, Cruz-Conty JE, Romero-Maroto J (2018) Micro-ureteroscopy vs. ureteroscopy: effects of miniaturization on renal vascularization and intrapelvic pressure. World J Urol 36(5):811–817. https://doi.org/10.1007/s00345-018-2205-y
11. Monga M, Bodie J, Ercole B (2004) Is there a role for small-diameter ureteral access sheaths? Impact on irrigant flow and intrapelvic pressures. Urology 64(3):439–441. https://doi.org/10.1016/j.urology.2004.04.060 **(discussion 441–432)**
12. Ng YH, Somani BK, Dennison A, Kata SG, Nabi G, Brown S (2010) Irrigant flow and intrarenal pressure during flexible ureteroscopy: the effect of different access sheaths, working channel instruments, and hydrostatic pressure. J Endourol 24(12):1915–1920. https://doi.org/10.1089/end.2010.0188
13. Emre Sener T, Cloutier J, Villa L, Marson F, Buttice S, Doizi S, Traxer O (2016) Can we provide low intrarenal pressures with good irrigation flow by decreasing the size of ureteral access sheaths? J Endourol 30(1):49–55. https://doi.org/10.1089/end.2015.0387
14. Sakhadeo NB, Venkatesh R, Trafford P, Parr NJ (1996) A new system of irrigation for ureteroscopy. Br J Urol 78(4):639–640
15. Lechevallier E, Luciani M, Nahon O, Lay F, Coulange C (2003) Transurethral ureterorenolithotripsy using new automated irrigation/suction system controlling pressure and flow compared with standard irrigation: a randomized pilot study. J Endourol 17(2):97–101. https://doi.org/10.1089/08927790360587423
16. Zhu X, Song L, Xie D, Peng Z, Guo S, Deng X, Liu S, Fan D, Huang J, Liu T, Du C, Zhu L, Yang Z, Peng G, Hu M, Yao L, Zeng M, Zhong J, Qing W, Ye Z (2016) Animal experimental study to test application of intelligent pressure control device in monitoring and control of renal pelvic pressure during flexible ureteroscopy. Urology. https://doi.org/10.1016/j.urology.2016.02.022
17. Huang J, Xie D, Xiong R, Deng X, Huang C, Fan D, Peng Z, Qin W, Zeng M, Song L (2018) The application of suctioning flexible ureteroscopy with intelligent pressure control in treating upper urinary tract calculi on patients with a solitary kidney. Urology 111:44–47. https://doi.org/10.1016/j.urology.2017.07.042
18. De S, Torricelli FC, Sarkissian C, Kartha G, Monga M (2014) Evaluating the automated thermedx fluid management system

in a ureteroscopy model. J Endourol 28(5):549–553. https://doi.org/10.1089/end.2013.0697
19. Blew BD, Dagnone AJ, Pace KT, Honey RJ (2005) Comparison of Peditrol irrigation device and common methods of irrigation. J Endourol 19(5):562–565. https://doi.org/10.1089/end.2005.19.562
20. Suh LK, Rothberg MB, Landman J, Katsumi H, Gupta M (2010) Intrarenal pressures generated during deployment of various antiretropulsion devices in an ex vivo porcine model. J Endourol 24(7):1165–1168. https://doi.org/10.1089/end.2010.0118
21. Michel MS, Honeck P, Alken P (2008) Conventional high pressure versus newly developed continuous-flow ureterorenoscope: urodynamic pressure evaluation of the renal pelvis and flow capacity. J Endourol 22(5):1083–1085. https://doi.org/10.1089/end.2008.0016
22. Saltzman B, Khasidy LR, Smith AD (1987) Measurement of renal pelvis pressures during endourologic procedures. Urology 30(5):472–474
23. Goble NM, Hammonds JC (1987) An in vitro study of intracavitary pressures during percutaneous nephrolithotomy. Br J Urol 60(4):307–311
24. Low RK (1999) Nephroscopy sheath characteristics and intrarenal pelvic pressure: human kidney model. J Endourol 13(3):205–208. https://doi.org/10.1089/end.1999.13.205
25. Troxel SA, Low RK (2002) Renal intrapelvic pressure during percutaneous nephrolithotomy and its correlation with the development of postoperative fever. J Urol 168(4 Pt 1):1348–1351. https://doi.org/10.1097/01.ju.0000030996.64339.f1
26. Guohua Z, Wen Z, Xun L, Wenzhong C, Yongzhong H, Zhaohui H, Ming L, Kaijun W (2007) The influence of minimally invasive percutaneous nephrolithotomy on renal pelvic pressure in vivo. Surg Laparosc Endosc Percutaneous Tech 17(4):307–310. https://doi.org/10.1097/SLE.0b013e31806e61f4
27. Zhong W, Zeng G, Wu K, Li X, Chen W, Yang H (2008) Does a smaller tract in percutaneous nephrolithotomy contribute to high renal pelvic pressure and postoperative fever? J Endourol 22(9):2147–2151. https://doi.org/10.1089/end.2008.0001
28. Tepeler A, Akman T, Silay MS, Akcay M, Ersoz C, Kalkan S, Armagan A, Sarica K (2014) Comparison of intrarenal pelvic pressure during micro-percutaneous nephrolithotomy and conventional percutaneous nephrolithotomy. Urolithiasis 42(3):275–279. https://doi.org/10.1007/s00240-014-0646-3
29. Mager R, Balzereit C, Reiter M, Gust K, Borgmann H, Husch T, Nagele U, Haferkamp A, Schilling D (2015) Introducing a novel in vitro model to characterize hydrodynamic effects of percutaneous nephrolithotomy systems. J Endourol 29(8):929–932. https://doi.org/10.1089/end.2014.0854
30. Landman J, Venkatesh R, Ragab M, Rehman J, Lee DI, Morrissey KG, Monga M, Sundaram CP (2002) Comparison of intrarenal pressure and irrigant flow during percutaneous nephroscopy with an indwelling ureteral catheter, ureteral occlusion balloon, and ureteral access sheath. Urology 60(4):584–587
31. Alsyouf M, Abourbih S, West B, Hodgson H, Baldwin DD (2018) Elevated renal pelvic pressures during percutaneous nephrolithotomy risk higher postoperative pain and longer hospital stay. J Urol 199(1):193–199. https://doi.org/10.1016/j.juro.2017.08.039
32. Loftus CJ, Hinck B, Makovey I, Sivalingam S, Monga M (2018) Mini versus standard percutaneous nephrolithotomy: the impact of sheath size on intrarenal pelvic pressure and infectious complications in a porcine model. J Endourol 32(4):350–353. https://doi.org/10.1089/end.2017.0602
33. Nagele U, Horstmann M, Sievert KD, Kuczyk MA, Walcher U, Hennenlotter J, Stenzl A, Anastasiadis AG (2007) A newly designed amplatz sheath decreases intrapelvic irrigation pressure during mini-percutaneous nephrolitholapaxy: an in vitro pressure-measurement and microscopic study. J Endourol 21(9):1113–1116. https://doi.org/10.1089/end.2006.0230
34. Nicklas AP, Schilling D, Bader MJ, Herrmann TR, Nagele U (2015) The vacuum cleaner effect in minimally invasive percutaneous nephrolitholapaxy. World J Urol. https://doi.org/10.1007/s00345-015-1541-4
35. Nagele U, Walcher U, Bader M, Herrmann T, Kruck S, Schilling D (2015) Flow matters 2: how to improve irrigation flow in small-calibre percutaneous procedures—the purging effect. World J Urol. https://doi.org/10.1007/s00345-015-1486-7
36. Song L, Chen Z, Liu T, Zhong J, Qin W, Guo S, Peng Z, Hu M, Du C, Zhu L, Yao L, Yang Z, Huang J, Xie D (2011) The application of a patented system to minimally invasive percutaneous nephrolithotomy. J Endourol 25(8):1281–1286. https://doi.org/10.1089/end.2011.0032
37. Yang Z, Song L, Xie D, Deng X, Zhu L, Fan D, Peng Z, Guo S, Ye Z (2016) The new generation mini-PCNL system—monitoring and controlling of renal pelvic pressure by suctioning device for efficient and safe PCNL in managing renal staghorn calculi. Urol Int. https://doi.org/10.1159/000442002
38. Wanajo I, Tomiyama Y, Yamazaki Y, Kojima M, Shibata N (2004) Pharmacological characterization of beta-adrenoceptor subtypes mediating relaxation in porcine isolated ureteral smooth muscle. J Urol 172(3):1155–1159. https://doi.org/10.1097/01.ju.0000133557.39515.b6
39. Tomiyama Y, Hayakawa K, Shinagawa K, Akahane M, Ajisawa Y, Park YC, Kurita T (1998) Beta-adrenoceptor subtypes in the ureteral smooth muscle of rats, rabbits and dogs. Eur J Pharmacol 352(2–3):269–278
40. Park YC, Tomiyama Y, Hayakawa K, Akahane M, Ajisawa Y, Miyatake R, Kiwamoto H, Sugiyama T, Kurita T (2000) Existence of a beta3-adrenoceptro and its functional role in the human ureter. J Urol 164(4):1364–1370
41. Selmy GI, Hassouna MM, Khalaf IM, Elhilali MM (1994) Effects of verapamil, prostaglandin F2 alpha, phenylephrine, and noradrenaline on upper urinary tract dynamics. Urology 43(1):31–35
42. Holst U, Dissing T, Rawashdeh YF, Frokiaer J, Djurhuus JC, Mortensen J (2003) Norepinephrine inhibits the pelvic pressure increase in response to flow perfusion. J Urol 170(1):268–271. https://doi.org/10.1097/01.ju.0000069824.13258.14
43. Holst U, Rawashdeh YF, Andreasen F, Christian Djurhuus J, Mortensen J (2005) Endoluminal pelvic perfusion with norepinephrine causes only minor systemic effects and diminishes the increase in pelvic pressure caused by perfusion. Scand J Urol Nephrol 39(6):443–448. https://doi.org/10.1080/00365590500221469
44. Jakobsen JS, Holst U, Jakobsen P, Steen W, Mortensen J (2007) Local and systemic effects of endoluminal pelvic perfusion of isoproterenol: a dose response investigation in pigs. J Urol 177(5):1934–1938. https://doi.org/10.1016/j.juro.2007.01.020
45. Mortensen J, Holst U, Jakobsen JS, Andreasen F (2008) Endoluminal norepinephrine inhibits smooth muscle activity of the pig pyeloureter by stimulation of beta-adrenoceptors without side effects. Basic Clin Pharmacol Toxicol 103(5):455–460. https://doi.org/10.1111/j.1742-7843.2008.00297.x
46. Jung HU, Jakobsen JS, Mortensen J, Osther PJ, Djurhuus JC (2008) Irrigation with isoproterenol diminishes increases in pelvic pressure without side-effects during ureterorenoscopy: a randomized controlled study in a porcine model. Scand J Urol Nephrol 42(1):7–11. https://doi.org/10.1080/00365590701520073
47. Jakobsen JS, Jung HU, Gramsbergen JB, Osther PJ, Walter S (2010) Endoluminal isoproterenol reduces renal pelvic pressure during semirigid ureterorenoscopy: a porcine model. BJU Int 105(1):121–124. https://doi.org/10.1111/j.1464-410X.2009.08678.x