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Original Article

Effects of micro-channel negative pressure sheath percutaneous nephrolithotomy versus extracorporeal shock wave lithotripsy for renal stones: risk factors for postoperative complications

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Abstract: Objective: To compare the effects of micro-channel negative pressure sheath percutaneous nephrolithotomy (mPCNL) and extracorporeal shock wave lithotripsy (ESWL) in the treatment of renal stones and analyze risk factors for postoperative complications. Methods: A retrospective analysis was conducted on 120 patients with renal stones treated at Beijing Friendship Hospital from January 2023 to December 2024. Patients were divided into two groups: control (ESWL, n=60) and observation (mPCNL, n=60). Clinical efficacy, renal injury markers, inflammatory factors, oxidative stress markers, quality of life, and complications were compared. Risk factors for complications were assessed by dividing patients into good and poor outcome groups based on complications within 30 days post-surgery. Results: The observation group showed a significantly higher clinical efficacy rate than the control group ($P<0.05$). Renal injury and inflammatory markers increased 24 hours post-surgery in both groups, with the control group showing a more significant rise. Oxidative stress markers also showed a greater change in the control group ($P<0.05$). At 30 days post-surgery, quality of life improved more significantly in the observation group ($P<0.05$). The total complication rate was lower in the observation group ($P<0.05$). Multivariate analysis identified age, surgical method, stone diameter, catheter indwelling time, renal insufficiency, and diabetes as independent risk factors for complications (all $P<0.05$). Conclusion: mPCNL was more effective than ESWL for renal stones treatment, with fewer complications and greater quality of life improvement. Age, surgical method, and stone diameter were independent risk factors for postoperative complications.

Keywords: Renal stones, micro-channel negative pressure sheath percutaneous nephrolithotomy, extracorporeal shock wave lithotripsy, comparative study, complications, risk factors

Introduction

Renal stones, formed by supersaturated precipitation of lithogenic substances in urine, are among the most common urinary system diseases [1]. The incidence of renal stones has been rising annually, closely related to metabolic abnormalities, dietary habits, genetic factors, and geographical environment [2]. The typical clinical manifestations include sudden lumbar and abdominal colic and hematuria. Without timely intervention, renal stones can lead to urinary tract obstruction, recurrent infection, and even renal insufficiency, and lower quality of life [3].

Currently, clinical treatments for renal stones primarily include extracorporeal shock wave lithotripsy (ESWL) and minimally invasive techniques such as micro-channel negative pressure sheath percutaneous nephrolithotomy (mPCNL) [4]. ESWL is a non-invasive method that uses high-energy shock waves focused on the stone to break it up, allowing fragments to pass naturally through urine [5]. However, factors such as stone composition, location, and anatomical structures can significantly affect the stone clearance rate [6]. Some patients require multiple treatments to achieve optimal results, and complications such as stone street

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formation, renal colic, and renal insufficiency may occur postoperatively [7].

mPCNL, a modified version of traditional percutaneous nephrolithotomy (PCNL), uses a thinner channel (usually F14-F18) combined with a negative pressure suction system. This technique effectively removes stone fragments during lithotripsy while reducing renal pelvic pressure, thereby lowering the risk of infection and bleeding [8]. Compared to standard PCNL, mPCNL offers advantages such as less trauma, faster postoperative recovery, and a higher stone clearance rate. However, it presents greater technical challenges and risks, including intraoperative bleeding and injury to the collecting system [9].

Although both mPCNL and ESWL are widely used in clinical practice, comparative studies on their efficacy in treating renal stones remain limited. The advantages of each in terms of surgical safety and postoperative complications are uncertain [10]. Furthermore, postoperative complications for both procedures are influenced by patient-specific factors, stone characteristics, and surgical techniques, requiring further investigation into the relevant risk factors [11]. Therefore, this study aimed to compare the clinical efficacy of mPCNL and ESWL in treating renal stones and to identify independent risk factors for postoperative complications. The goal was to provide scientific evidence to guide clinicians in selecting treatment options, improving patient outcomes and quality of life, reducing medical risks, and advancing kidney stone treatment.

Materials and methods

Participants

This retrospective study analyzed clinical data from 120 patients with renal stones admitted to Beijing Friendship Hospital, affiliated with Capital Medical University, from January 2023 to December 2024. Patients were divided into two groups based on the surgical method: control group (n=60, ESWL) and observation group (n=60, mPCNL).

Inclusion criteria: (1) Renal stones diagnosed by imaging and clinical evaluation, unilateral in nature. (2) Treatment with mPCNL or ESWL. (3) No prior history of urinary surgery.

Exclusion criteria: (1) Severe ureteral obstruction or stenosis. (2) Severe coagulation dysfunction. (3) History of severe urinary trauma. (4) Cardiovascular and cerebrovascular diseases, or failure of heart and lung organs. (5) Mental disorders. (6) Incomplete clinical data.

This study was approved by the Medical Ethics Committee of Beijing Friendship Hospital, Capital Medical University (batch number: 2025217).

Sample size estimation

Sample size was estimated using PASS software. Based on preliminary data (α=0.05, β=0.20, P1=0.70, P2=0.90), 61 patients per group were required. The final sample size was adjusted to 60 patients per group.

Surgical methods

Both groups underwent routine preoperative examinations, symptomatic treatment, and initial assessment of stone location and size.

Control group: Patients were treated with ESWL without anesthesia. They were placed in a supine position on the treatment table, and the procedure was monitored by B-mode ultrasound. A hydraulic and electric B-mode ultrasonic positioning lithotripter (CS-2000A, Suzhou Xixin Company) was used with the following parameters: voltage 3.5-6.5 kV, energy 5-13 W, and frequency 60-70 shocks/min. Shock wave energy was initiated at the minimum setting and gradually increased as needed, not exceeding 13 W.

Postoperatively, a computed tomography (CT) scan of the urinary system was performed to assess stone clearance. If large residual stones were present, a second ESWL session could be scheduled. Patients were advised to increase fluid intake to more than 3000 mL/day to facilitate stone expulsion.

Observation group (mPCNL): Patients underwent mPCNL under anesthesia. In the lithotomy position, a 5Fr ureteral catheter was placed retrogradely under nephroscopy, and a 16Fr balloon catheter was placed in the bladder. Both catheters were secured with gauze.

Under color Doppler ultrasound guidance, percutaneous renal puncture was performed near the posterior axillary line. Success was confirmed by ultrasound. A guidewire was inserted through the needle, and the tract was dilated stepwise to an 18Fr micro-channel. The oblique tube of the negative-pressure sheath was connected to a stone collection bottle, and the other end of the bottle was connected to central negative pressure (maintained at 150-200 mmHg). The proximal straight tube was sealed with a rubber cap, and the negative-pressure sheath was connected to the renal collecting system via a percutaneous nephroscope. The stone was fragmented using a holmium laser, and the fragments and dust were cleared by irrigation fluid and negative pressure.

Observation indicators

General information: Demographic and clinical data were collected upon admission, including gender, age, body mass index (BMI), disease duration, educational level, place of residence, average monthly family income, and marital status.

Clinical efficacy: The therapeutic effect was evaluated postoperatively [12] and classified as follows: (1) Marked effect: Disappearance of clinical symptoms and signs, no hydronephrosis, negative urine routine, and no residual stones on imaging. (2) Effective: Significant improvement in clinical symptoms and signs compared with preoperatively. Imaging showed residual stones that were reduced in size or had migrated distally. (3) Ineffective: No significant improvement in symptoms or signs, and no change in stone size or location on imaging.

The total effective rate = (marked effect + effective)/total number of cases × 100%.

Renal injury markers: Venous blood (5 mL) was collected in the fasting state preoperatively and 24 hours postoperatively. Samples were centrifuged at 3000 rpm for 10 minutes. The serum was aliquoted into three parts. One aliquot was used to measure levels of neutrophil gelatinase-associated lipocalin (NGAL), creatinine (Cr), and blood urea nitrogen (BUN) using a Beckman Coulter AU5800 automatic biochemical analyzer.

Inflammatory factors: Another serum aliquot was used to determine the levels of C-reactive protein (CRP), tumor necrosis factor-α (TNF-α), and interleukin-6 (IL-6) by enzyme-linked immunosorbent assay (ELISA). Kits were purchased from the Nanjing Jianxeng Bioengineering Institute, and an EXL800 multifunctional microplate reader (Poten Company) was used.

Oxidative stress markers: The third serum aliquot was used to assess oxidative stress. Malondialdehyde (MDA) and superoxide dismutase (SOD) levels were detected by ELISA and the nitrite reduction method, respectively. Glutathione peroxidase (GSH-Px) levels were measured by colorimetry. Kits were purchased from Shanghai Enzyme Linked Biotechnology Co., Ltd. and Beijing Solaibao Technology Co., Ltd. All measurements were performed using an EXL800 multifunctional microplate reader (Poten Company).

Quality of life: The Short Form 36 Health Survey (SF-36) [13] was used to evaluate physical function, social role, emotional state, and vitality. Each dimension contains 10 items, scored from 0 to 10, with a total score of 100. Higher scores indicated better health status.

Complications: Incidence of fever, hematuria, pain, urinary tract infection, renal colic, and other complications within 30 days was recorded. Total incidence = (number of complications/total patients) × 100%.

Statistical methods

Data were analyzed using SPSS 23.0 and GraphPad Prism 8.0. The Shapiro-Wilk test assessed normality. Normally distributed data were expressed as mean ± standard deviation ($\bar{x} \pm sd$), while non-normally distributed data were presented as median (interquartile range). For normally distributed continuous variables, the independent t-test was used for group comparisons, and the Mann-Whitney U test (two groups) or Kruskal-Wallis H test (multiple groups) was used for non-normally distributed data. Categorical variables, expressed as counts and percentages, were compared using Pearson's chi-square test. Paired t-tests (normal data) or Wilcoxon signed rank tests (non-normal data) were used for intra-group comparisons. Univariate analysis ($P<0.05$) identified potential prognostic factors, and multivariate logistic regression was used to determine risk factors for complications. All statistical

Table 1. Comparison of general data between the two groups [n, (%), $\bar{x} \pm s$]

		Control group n=60	Observation group n=60	t/χ^2	*P*
Gender	Man	37 (61.67)	38 (63.33)	0.036	0.850
	Woman	23 (38.33)	22 (36.67)		
Age (years)	<60	28 (46.67)	34 (56.67)	0.061	0.806
	≥60	32 (53.33)	26 (43.33)		
BMI (kg/m^2)	≥24	23 (38.33)	25 (41.67)	0.139	0.709
	<24	37 (61.67)	35 (58.33)		
Disease duration (months)		8.45±3.62	8.80±3.19	0.562	0.575
Degree of education	College or below	39 (65.00)	37 (61.67)	0.144	0.705
	High school and above	21 (35.00)	23 (38.33)		
Place of residence	City	26 (43.33)	31 (51.67)	0.835	0.361
	Township	34 (56.67)	29 (48.33)		
Average monthly household income	≤5000 yuan	29 (48.33)	27 (45.00)	0.134	0.714
	>5000 yuan	31 (51.67)	33 (55.00)		
Marital status	Unmarried	17 (28.33)	16 (26.67)	0.563	0.755
	Married	35 (58.33)	33 (55.00)		
	Divorced/widowed	8 (13.33)	11 (18.33)		
Stone diameter (cm)	<2.5	29 (48.33)	35 (58.33)	1.205	0.272
	≥2.5	31 (51.67)	25 (41.67)		
Types of stones	Renal pelvic Calculi	25 (41.67)	18 (30.00)	1.776	0.412
	Calyceal calculi	25 (41.67)	30 (50.00)		
	Staghorn calculi	10 (16.67)	12 (20.00)		
Postoperative catheter indwelling time (d)	≤5	32 (53.33)	36 (60.00)	0.543	0.461
	>5	28 (46.67)	24 (40.00)		
Renal insufficiency	No	43 (71.67)	41 (68.33)	0.159	0.690
	Yes	17 (28.33)	19 (31.67)		
Hypertension	No	41 (68.33)	37 (61.67)	0.586	0.444
	Yes	19 (31.67)	23 (38.33)		
Diabetes	No	32 (53.33)	27 (45.00)	0.834	0.361
	Yes	28 (46.67)	33 (55.00)		

Table 2. Comparison of clinical efficacy between the two groups of patients (n, %)

Group	n	Marked effect	Effective	Ineffectiveness	Total effective
Control group	60	21 (35.00)	25 (41.67)	14 (23.33)	46 (76.67)
Observation group	60	32 (53.33)	23 (38.33)	5 (8.33)	55 (91.67)
χ^2					6.630
P					0.036

tests were two-sided, with P<0.05 considered significant.

Results

Comparison of the general data

There were no significant differences in the general data between the two groups of patients, and they were comparable (P>0.05). See **Table 1**.

Comparison of clinical efficacy

The clinical efficacy rate in the observation group was 91.67%, significantly higher than 76.67% in the control group (P<0.05). See **Table 2**.

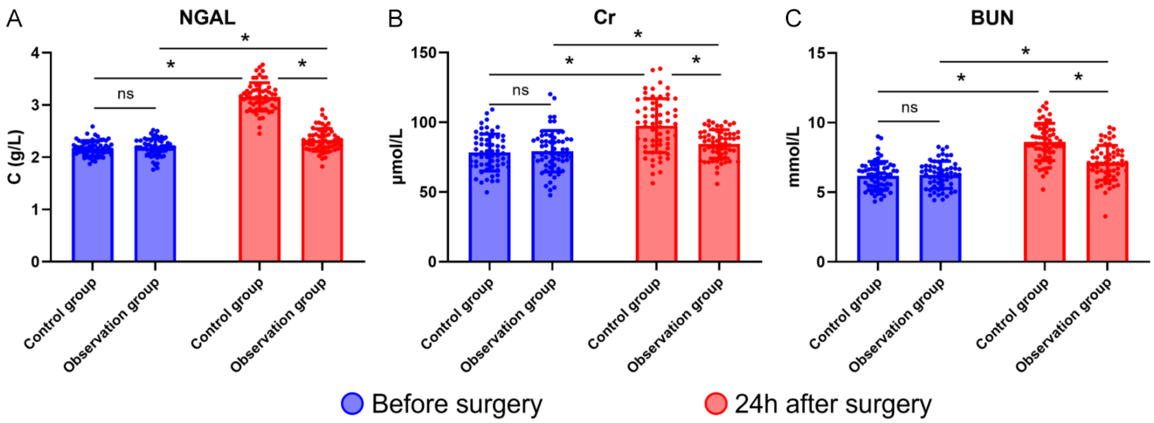

Figure 1. Renal injury markers of the two groups of patients. A. NGAL; B. Cr; C. BUN. NGAL, Gelatinase-associated lipocalin; Cr, Creatinine; BUN, Blood urea nitrogen. *P<0.05; ns, not significant.

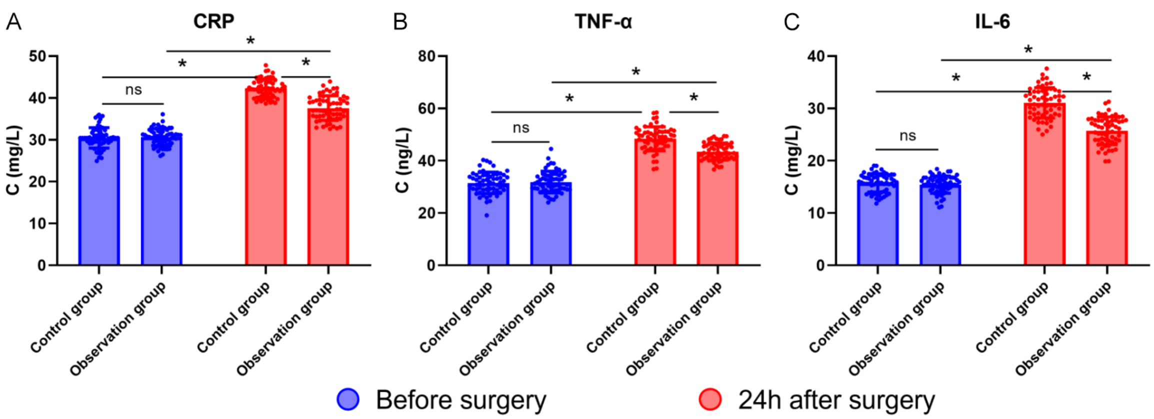

Figure 2. Indicators of inflammatory factors of the two groups of patients. A. CRP; B. TNF-α; C. IL-6. CRP, C-reactive protein; TNF-α, Tumor necrosis factor-α; IL-6, Interleukin-6. *P<0.05; ns, not significant.

Comparison of renal injury markers

Before surgery, there were no significant differences in renal injury factors (NGAL, Cr, BUN) between the two groups (all P>0.05). However, 24 hours post-surgery, both groups showed increased renal injury markers, with a more significant increase observed in the control group (all P<0.05). See **Figure 1**.

Comparison of inflammatory factor indicators

Before surgery, no significant differences in inflammatory factors (CRP, TNF-α, IL-6) were found between the groups (all P>0.05). At 24 hours post-surgery, inflammatory factors increased in both groups, with a more pronounced increase in the control group (P<0.05) (**Figure 2A-C**).

Comparison of oxidative stress markers

Before surgery, there were no significant differences in oxidative stress markers between two groups (all P>0.05). At 24 hours post-surgery, levels of SOD and GSH-Px decreased, while MDA levels increased, with the changes being more significant in the control group (all P<0.05). See **Figure 3A-C**.

Comparison of quality of life

Before surgery, there were no significant differences in quality of life between the groups (all P>0.05). At 30 days post-surgery, quality of life scores increased in both groups, but the increase was significantly greater in the observation group (all P<0.05), whereas the control group showed no significant improvement (all P<0.05). See **Figure 4A-H**.

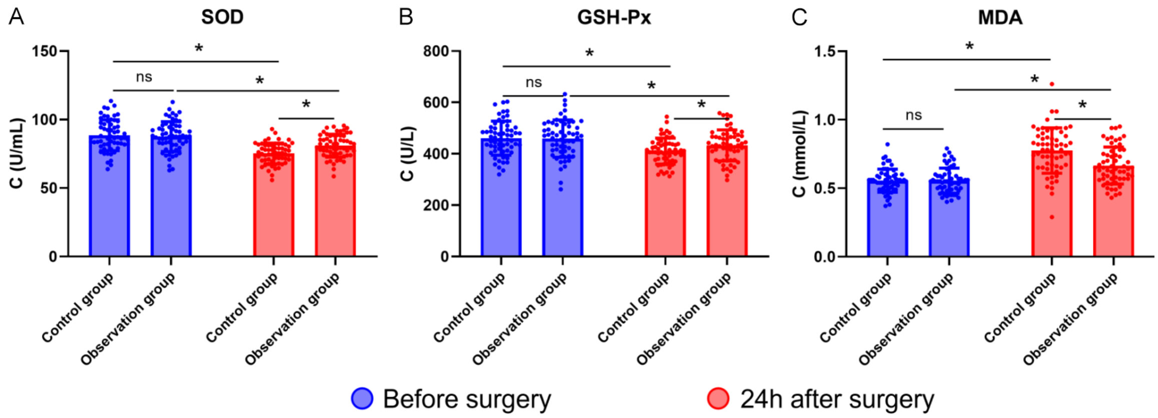

Figure 3. Oxidative stress markers of the two groups of patients. A. SOD; B. GSH-Px; C. MDA. SOD, Superoxide dismutase; GSH-Px, Glutathione peroxidase; MDA, Malondialdehyde. *P<0.05; ns, not significant.

Comparison of complications

The total incidence of complications was 48.33% in the control group and 21.67% in the observation group. The incidence in the observation group was significantly lower than in the control group (P<0.05). See **Table 3**.

Univariate analysis

Based on the occurrence of complications, patients were divided into good and poor outcome groups. There were significant differences in age, surgical method, stone diameter, stone type, postoperative catheter indwelling time, renal insufficiency, and diabetes between the good and poor outcome groups (all P<0.05). See **Table 4**.

Multivariate analysis

Multivariate analysis of statistically significant factors from the univariate analysis showed that age, surgical method, stone diameter, postoperative catheter indwelling time, renal insufficiency, and diabetes were independent risk factors for postoperative complications (all P<0.05). See **Table 5**.

Discussion

The formation of renal stones is closely associated with metabolic abnormalities. When metabolic disorders cause excessive saturation of oxalic acid, calcium, and other substances in the urine, these components gradually precipitate and form a crystalline core, eventually developing into stones [14]. The clinical manifestations of stones are influenced by their size and shape. Large, irregular stones can obstruct the urinary tract or injure the mucosa, leading to renal colic, hematuria, and, in severe cases, impaired renal function [15]. Therefore, treatment strategies must aim to minimize the disease's effect on the patient's life. Among various treatment options, ESWL offers significant advantages over traditional open surgery by reducing patient pain, shortening operation time, and completely crushing large stones. Minimally invasive surgery is the preferred treatment for renal stones. With the development of percutaneous nephroscopic ultrasonic lithotripsy, it has become the first-line treatment for renal stones. Unlike traditional holmium laser lithotripsy or liquid point lithotripsy, percutaneous ultrasonic lithotripsy avoids thermal effects, thereby reducing kidney injury. Recently, the application of negative pressure technology in ultra-fine percutaneous nephroscopy by Chen et al. [16] has gained recognition in China. This study compared the clinical efficacy of mPCNL and ESWL, showing that the clinical efficacy rate of the observation group was significantly higher than that of the control group, providing strong evidence for efficacy of mPCNL.

The study results revealed that 24 hours after mPCNL, renal injury markers were significantly lower compared to those after ESWL, indicating that mPCNL has a more protective effect on renal function. This difference can be attributed to the distinct injury mechanisms of the two surgical methods. First, mPCNL uses a smaller F16-F22 microchannel, which significantly re-

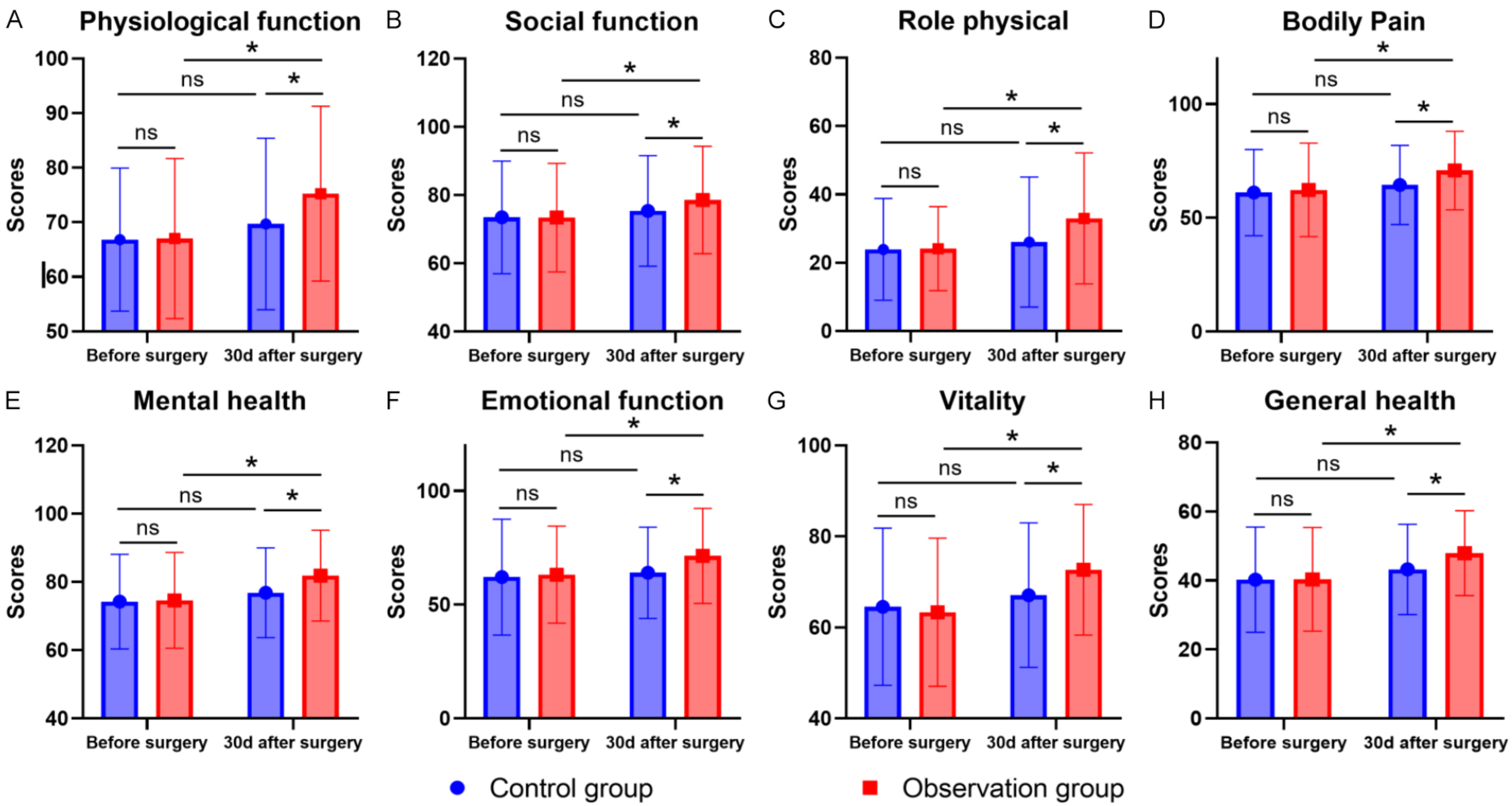

Figure 4. Quality of life in the two groups of patients. A. Physiological function; B. Social function; C. Role physical; D. Bodily pain; E. Mental health; F. Emotional function; G. Vitality; H. General health. *P<0.05; ns, not significant.

Table 3. Occurrence of complications in the two groups of patients (n, %)

Group	n	Fever	Hematuria	Pain	Urinary tract infections	Renal colic	Total occurrence
Control group	60	7 (11.67)	8 (13.33)	4 (6.67)	3 (5.00)	8 (13.33)	29 (48.33)
Observation group	60	3 (5.00)	1 (1.67)	4 (6.67)	1 (1.67)	4 (6.67)	13 (21.67)
X^2							12.652
P							0.027

Table 4. Univariate analysis (n, %)

		Good group (n=78)	Poor group (n=42)	X^2	*P*
Gender	Man	48 (61.54)	27 (64.29)	0.088	0.767
	Woman	30 (38.46)	15 (35.71)		
Age (years)	<60	47 (60.26)	15 (35.71)	6.585	0.010
	≥60	31 (39.74)	27 (64.29)		
BMI (kg/m^2)	≥24	27 (34.62)	21 (50.00)	2.692	0.101
	<24	51 (65.38)	21 (50.00)		
Surgical method	mPCNL	47 (60.26)	13 (30.95)	9.377	0.002
	ESWL	31 (39.74)	29 (69.05)		
Stone diameter (cm)	<2.5	50 (64.10)	14 (33.33)	10.385	0.001
	≥2.5	28 (35.90)	28 (66.67)		
Stone location	One side	37 (47.44)	15 (35.71)	1.528	0.217
	Bilateral	41 (52.56)	27 (64.29)		
Number of stones	Single	53 (67.95)	28 (66.67)	0.021	0.886
	Multiple	25 (32.05)	14 (33.33)		
Types of stones	Renal pelvic Calculi	29 (37.18)	14 (33.33)	7.169	0.028
	Calyceal calculi	40 (51.28)	15 (35.71)		
	Staghorn calculi	9 (11.54)	13 (30.95)		
Postoperative catheter indwelling time (d)	≤5	37 (47.44)	31 (73.81)	7.733	0.005
	>5	41 (52.56)	11 (26.19)		
Hydronephrosis of kidney	No	36 (46.15)	17 (40.48)	0.357	0.550
	Yes	42 (53.85)	25 (59.52)		
Renal insufficiency	No	60 (76.92)	24 (57.14)	6.270	0.012
	Yes	18 (23.08)	18 (42.86)		
History of renal surgery	No	67 (85.90)	34 (80.95)	0.501	0.479
	Yes	11 (14.10)	8 (19.05)		
Hypertension	No	56 (71.79)	27 (64.29)	0.722	0.396
	Yes	22 (28.21)	15 (35.71)		
Diabetes	No	48 (61.54)	11 (26.19)	13.648	0.000
	Yes	30 (38.46)	31 (73.81)		
History of smoking	No	42 (53.85)	23 (54.76)	0.009	0.924
	Yes	36 (46.15)	19 (45.24)		
History of alcohol consumption	No	45 (57.69)	27 (64.29)	0.495	0.482
	Yes	33 (42.31)	15 (35.71)		

duces puncture-related mechanical damage. Studies have shown that the area of renal parenchymal injury was reduced by approximately 50% compared to conventional PCNL [17]. Additionally, the fine operation channel and negative pressure suction system allow for precise stone removal while minimizing thermal damage to surrounding renal tissue. In con-

Table 5. Multivariate analysis

		B	*S.E.*	*Z*	*P*	*OR*	95% *CI*
Age (years)	<60						
	≥60	1.112	0.566	1.965	0.049	3.042	1.003-9.227
Surgical method	mPCNL						
	ESWL	1.548	0.524	2.956	0.003	4.703	1.685-13.126
Stone diameter (cm)	<2.5						
	≥2.5	1.067	0.509	2.098	0.036	2.908	1.073-7.881
Types of stones	Renal pelvic Calculi						
	Calyceal calculi	-0.479	0.563	-0.850	0.395	0.620	0.205-1.869
	Staghorn calculi	0.607	0.686	20.884	0.376	1.835	0.478-7.046
Postoperative catheter indwelling time (d)	≤5						
	>5	1.260	0.536	-2.349	0.019	0.284	0.099-0.812
Renal insufficiency	No						
	Yes	1.230	0.558	2.204	0.028	3.421	1.146-10.217
Diabetes	No						
	Yes	1.452	0.526	2.758	0.006	4.271	1.522-11.986

trast, although ESWL is non-invasive, its high-energy shock waves cause cavitation and shear forces that result in multiple forms of damage. These forces cause mechanical damage to renal parenchyma and induce oxidative stress, leading to the production of oxygen free radicals, which damage renal tubular epithelial cells. This injury has cumulative effects, with repeated treatments increasing the risk of renal damage [18]. Studies have shown that renal blood flow is reduced by 30% and the excretion of intravenous contrast agents is delayed immediately after ESWL, with injury severity positively correlated with the number of shock waves [7, 19, 20]. Therefore, mPCNL offers clear advantages in renal function protection. It allows for single-session stone treatment, avoiding repeated injury, and the negative pressure suction system reduces renal pelvic pressure, thereby minimizing mechanical kidney damage [21, 22]. Thus, mPCNL is an ideal treatment option for patients with solitary kidneys, chronic kidney disease, or other conditions requiring renal function preservation.

The body injury caused by renal stones and the stress response to surgery can alter the body's inflammatory profile [23]. Among these, CRP, TNF-α, and IL-6 are sensitive markers reflecting stress and microinflammation. CRP, an acute-phase protein synthesized by hepatocytes, rises sharply during inflammation [24]. As pro-inflammatory cytokines, TNF-α and IL-6 are acutely elevated under stress and correlate positively with the severity of inflammation [25, 26].

In our study, serum inflammatory markers increased in both groups at 24 hours postoperatively, but the rise was more pronounced in the ESWL group. This aligns with previous findings showing that inflammatory factor levels increase more significantly after ESWL, especially following multiple sessions [27]. Reportedly, renal blood flow can decrease by approximately 30% immediately after ESWL, accompanied by a significant postoperative rise in inflammatory factors [28].

Possible mechanisms include: (1) Shock wave-induced cavitation and shear stress directly damage renal parenchyma, expose basement membrane collagen, and activate the platelet and complement systems [29]. (2) Free radicals generated during lithotripsy induce lipid peroxidation [30]. (3) Secondary injury to the urothelium caused by passing stone fragments [31].

In contrast, mPCNL minimizes damage to healthy tissue through precise endoluminal manipulation. Its real-time irrigation system reduces renal pelvic pressure, limits bacterial and endotoxin absorption, and clears stones, thereby removing persistent inflammatory stimuli [32]. Notably, the negative pressure suction system effectively lowers intrapelvic pressure and reduces the release of inflammatory mediators into the systemic circulation, which may explain its milder inflammatory response.

The dynamic balance of the oxidant-antioxidant system is crucial in the surgical stress response [33]. Surgical stress promotes the production of reactive oxygen and nitrogen species, disrupting this balance [34]. MDA is a marker of lipid peroxidation, while SOD is a key antioxidant enzyme. Both are widely used clinically to assess oxidative stress [35]. GSH-Px plays a central role in maintaining cellular redox homeostasis by scavenging hydrogen peroxide and lipid peroxides using GSH. Decreased GSH-Px activity often indicates depletion of antioxidant reserves [36].

Our study found that SOD and GSH-Px levels decreased, and MDA levels increased, at 24 hours postoperatively in both groups, with a more significant trend after ESWL. This difference stems from the distinct mechanisms of the two procedures. The cavitation effect in ESWL directly causes lipid peroxidation of cell membranes and activates the xanthine oxidase system. The ischemia-reperfusion process resulting from microvascular injury leads to massive reactive oxygen species leakage from the mitochondrial electron transport chain. Together with the "respiratory burst" of inflammatory cells, these factors create a systemic, self-amplifying cycle of oxidative stress [37]. In contrast, mPCNL induces localized oxidative stress through limited surgical trauma and energy deposition. The precision of modern microchannel technology and negative pressure suction effectively contain the injury, confining the oxidative stress response mostly to the surgical area for a shorter duration [38]. This explains why the fluctuations in renal function indices are more significant after ESWL and suggests caution when selecting treatment for patients with poor baseline antioxidant capacity.

At 30 days postoperatively, quality of life was significantly improved in the observation group compared with the control group. Although ESWL avoids a surgical incision, its recovery has limitations. Shock waves can damage renal parenchyma and surrounding tissues, causing flank pain or hematuria that may last days to weeks. mPCNL removes stones directly through a minimally invasive tract. Postoperative pain mainly originates from the percutaneous access site, but this typically resolves within 3-5 days with effective analgesia [32].

Furthermore, mPCNL patients usually have their nephrostomy tube removed within 24-48 hours and can resume light activities within a week. In contrast, ESWL patients often need to avoid strenuous exercise for 2-4 weeks while awaiting stone passage [39]. Psychologically, the definitive nature of mPCNL reduces anxiety about residual stones, whereas ESWL patients face multiple follow-up visits and potential retreatment, increasing their psychological burden. Studies have shown that mPCNL patients typically return to work within 7-10 days, compared with 2-4 weeks for ESWL patients due to repeated visits and the uncertainty of stone expulsion [40]. Therefore, mPCNL's high stone-free rate, lower re-intervention rate, and shorter symptom resolution time are its core advantages in improving patients' quality of life.

Complication analysis revealed that the total incidence of complications was significantly lower in the mPCNL group compared to the ESWL group. Multivariate analysis identified independent risk factors for postoperative complications, including age, surgical method, stone diameter, postoperative catheter indwelling time, renal insufficiency, and diabetes. These factors interact to significantly influence the incidence and severity of postoperative complications. With aging, tissue repair ability decreases, immune function weakens, and the risk of infection increases. Elderly patients often have underlying conditions like hypertension and coronary heart disease, which reduce surgical tolerance and increase postoperative recovery time, leading to a higher risk of complications. Giulioni et al. [41] found that the overall incidence of complications in elderly patients (≥65 years) was 46.5%, compared to 34.5% in younger patients (<65 years).

Surgical methods also play a role in the incidence of complications. ESWL uses shock waves to break stones, but excessive or repeated energy can damage kidney tissue [42]. Stone fragments may obstruct the ureter, forming a "stone street" that can lead to renal colic, infections, and renal function damage. The duration of catheter indwelling time significantly impacts complication rates. Longer catheter indwelling increases the risk of urinary tract infections, as catheters can become a conduit for bacteria, leading to infections like cystitis or pyelonephritis. Prolonged catheter use can also irritate the bladder mucosa, causing discomfort such as frequent urination, urgency, and pain, which worsens quality of life [43].

Renal insufficiency is often caused by urinary tract obstruction. Long-term obstruction reduces the glomerular filtration rate, leading to the accumulation of metabolites such as guanidinosuccinic acid and methylguanidine [44]. In the uremic state, these and other retained toxins can decrease platelet counts and inhibit the expression of platelet factor III, thereby increasing vascular wall permeability and significantly elevating the risk of postoperative bleeding.

Diabetes mellitus is an important independent risk factor for postoperative infection in patients with renal stones. Studies have shown that the postoperative infection rate in diabetic patients is approximately 1.5 times higher than in non-diabetic patients [45]. This is primarily because the interaction between advanced glycation end products (AGEs) and their receptor (RAGE) activates nuclear factor κB (NF-κB), leading to increased secretion of IL-6. This triggers a chronic inflammatory response, impairs immune function, and delays wound healing [46].

In addition, hyperglycemia can reduce the chemotactic ability of neutrophils, further weakening the body's defenses against pathogens and significantly increasing the postoperative infection rate. Moreover, the microvascular complications of diabetes, including increased vascular wall fragility, can elevate the risk of intraoperative bleeding, which in turn may affect postoperative recovery. These findings provide an important reference for clinical risk assessment and individualized treatment planning.

This study also has some limitations. A small sample size, which may have affected the generalizability of the results; a short follow-up period, preventing comprehensive long-term evaluations; and a single-center design, which may introduce selection bias. Moreover, not all potential influencing factors were included, and the operational experience of different surgeons may have affected the results. Future studies should involve larger sample sizes, extended follow-up periods, multicenter trials, and further optimization of surgical techniques.

In conclusion, this study demonstrated the comprehensive advantages of mPCNL in treating upper urinary tract stones through a multidimensional comparison. mPCNL offers superior stone clearance, renal function protection, and effective control of inflammation and oxidative stress, leading to rapid improvement in quality of life. These findings provide strong evidence supporting mPCNL as a better treatment option, particularly for high-risk patients. Future research should focus on optimizing surgical techniques to expand indications and improve outcomes.

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Disclosure of conflict of interest

None.

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