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Dynamic Pulse Modulation During Ho:YAG Laser Lithotripsy: When to change from Magneto to Virtual Basket? Insights from a Multicenter Study

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Research Article

Keywords:

Posted Date: August 10th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10497388/v1

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Additional Declarations: No competing interests reported.

Abstract

Introduction

The introduction of pulse modulation technologies has expanded the versatility of high-power Holmium lasers. Magneto (M-Ho:YAG) pulse modulation provides low peak power and improved dusting characteristics, while Virtual Basket (VB) may enhance fragmentation efficiency in selected cases. However, the factors prompting intraoperative transition between these modalities remain poorly defined. This study aimed to identify the preoperative and intraoperative variables associated with the need to switch from M-Ho:YAG to VB during flexible ureteroscopy.

Methods

A multicenter observational study analyzed 400 consecutive patients undergoing retrograde intrarenal surgery between January 2025 and March 2026 using the Cyber Ho™ 150W platform. Lithotripsy was initiated with M-Ho:YAG in all cases. Patients were categorized into M-Ho:YAG-only (n=301) and M-Ho:YAG+VB (n=99) groups according to intraoperative pulse modulation strategy. Demographic, stone-related, anatomical, and procedural variables were evaluated.

Results

Mean stone volume was 1804 mm^3 and mean stone density was 938 HU. Among the 400 procedures, 99 patients (24.8%) required intraoperative transition from M-Ho:YAG to VB. Stone volume demonstrated a strong correlation with pulse modulation switching (r=0.69), indicating that larger stone burdens were more likely to require VB support. Lower pole stones represented the most frequent anatomical location among patients requiring modulation change. Furthermore, higher stone density was associated with an increased likelihood of switching, suggesting reduced dusting efficiency of low peak-power settings in harder stones.

Conclusions

Large stone burden, lower pole location, and high-density calculi appear to be the main predictors of intraoperative transition from M-Ho:YAG to VB. These findings support a dynamic pulse modulation strategy tailored to stone characteristics to optimize lithotripsy efficiency and procedural performance.

Introduction

Over the last decade, continuous technological progress in laser lithotripsy has been driven by the need to improve both intraoperative efficiency and postoperative outcomes during endourological procedures. Among the currently available energy sources, the Holmium:YAG (Ho:YAG) laser remains the gold standard for ureteroscopic and retrograde intrarenal surgery (RIRS) due to its proven efficacy across all stone compositions and clinical scenarios. Its mechanism of action is primarily based on a photothermal effect, in which laser energy is absorbed by water molecules contained within the stone,

leading to vaporization and subsequent fragmentation [1]. More recently, the Thulium Fiber Laser (TFL) has emerged as an alternative laser platform with several theoretical and practical advantages over conventional Ho:YAG systems. One of the major differences between both technologies lies in pulse architecture and peak power delivery. TFL produces a homogeneous rectangular-shaped pulse with significantly lower peak power, whereas conventional Ho:YAG lasers generate an asymmetric pulse characterized by an initial high-energy spike followed by rapid energy decay. Owing to its reduced peak power (approximately 500 W) TFL has demonstrated favorable dusting performance with lower stone retropulsion. In contrast, standard Ho:YAG systems may reach peak powers close to 10,000 W, which can increase fragment migration during lithotripsy [2]. In an attempt to optimize the performance of high-power Ho:YAG lasers while preserving their versatility and dusting efficacy, several pulse modulation technologies have been introduced in recent years. These innovations aim to modify the interaction between laser energy and the surrounding fluid environment by reshaping pulse emission profiles and reducing peak power through pulse elongation. By extending pulse duration, it is possible to achieve smoother energy delivery and improved stone stabilization, whereas shorter pulses generate higher peak power and greater fragmentation intensity [3]. Within this evolving technological landscape, novel pulse modulation modes such as Magneto Ho:YAG (M-Ho:YAG) and Virtual Basket (VB) have been developed to enhance lithotripsy efficiency and reduce retropulsion. M-Ho:YAG technology was specifically designed to reproduce some of the favorable dusting characteristics traditionally associated with TFL systems. By lowering peak power to approximately 500 W and prolonging pulse duration up to 2000 µs, this modulation mode seeks to improve stone stability, reduce retropulsion, and facilitate controlled fragmentation during the initial stages of lithotripsy [4]. Conversely, VB technology is based on a dual-pulse modulation strategy integrated into high-power Ho:YAG platforms. This emission mode generates sequential laser pulses intended to create a transient cavitation effect capable of partially limiting fragment migration while improving fine dusting efficiency. Additionally, the reduced stone displacement associated with this technology may facilitate fragment clearance and optimize intraoperative visibility during advanced stages of lithotripsy [5].

Despite these advantages, lower peak power technologies may present certain limitations when treating high-density stones. Low peak power lasers, including TFL and M-Ho:YAG, may exhibit reduced fragmentation efficiency and higher overall energy consumption when managing harder stones. In these scenarios, increasing peak power may enhance ablative capacity and improve fragmentation performance, particularly during the initial phases of lithotripsy when larger and harder stone burdens are encountered. Consequently, the balance between low retropulsion and adequate dusting efficiency has become a central topic in modern laser lithotripsy strategies. Although several studies have evaluated pulse modulation technologies independently, current evidence remains largely focused on static comparisons between different laser modes. However, laser lithotripsy represents a dynamic process in which stone morphology and dusting behavior continuously evolve throughout the procedure. Consequently, the optimal pulse modulation strategy may also vary according to stone density, dusting performance and intraoperative stone behavior.

In this context, the present multicenter study aimed to evaluate the intraoperative transition from M-Ho:YAG pulse modulation to VB pulse modulation during flexible ureteroscopy, while also identifying the preoperative stone-related and anatomical characteristics that may influence the need to modify pulse modulation strategies during endoscopic lithotripsy.

Material and Methods

Study Design and Patient Population

This multicenter observational real-world study analyzed prospectively collected data from 400 consecutive patients treated across five international high-volume endourological centers between January 2025 and March 2026. Adult patients undergoing RIRS for kidney stone disease using the high-power Cyber Ho 150 laser platform (Quanta System SpA, Milan, Italy) were included. The present study specifically focused on the subgroup of patients requiring intraoperative transition from M-Ho:YAG to VB pulse modulation with the objective of identifying the preoperative stone-related and anatomical characteristics, as well as intraoperative parameters, associated with the need for pulse modulation switching during endoscopic lithotripsy. Patients younger than 18 years or those with incomplete perioperative data were excluded from the analysis.

Surgical Technique and Laser Settings

All procedures were performed by experienced endourologists with an annual surgical volume exceeding 100 RIRS procedures per year. Flexible ureteroscopy was carried out according to standard institutional protocols using reusable or single-use flexible ureteroscopes depending on center availability and surgeon preference. Lithotripsy was systematically initiated using M-Ho:YAG pulse modulation as the default dusting strategy, with intraoperative switching to VB when Magneto proved ineffective. Initial laser settings generally ranged between 0.6–1.0 J and 10–20 Hz, using 272 µm laser fibers according to stone characteristics and surgeon preference. During the procedure, intraoperative transition from M-Ho:YAG to VB pulse modulation was allowed at the discretion of the operating surgeon in cases of perceived suboptimal dusting efficiency, excessive energy consumption, prolonged laser time or inadequate dusting efficacy. The Cyber Ho™ 150W platform enabled immediate pulse modulation transition through a single-console interface without requiring fiber replacement or equipment exchange. The use of retrieval baskets, dusting techniques, fragmentation strategies, suction techniques and auxiliary instruments remained entirely surgeon dependent.

Data Collection and Definitions

Preoperative demographic and clinical variables included age, sex, body mass index (BMI), American Society of Anesthesiologists (ASA) score, baseline hemoglobin, serum creatinine, and estimated glomerular filtration rate (eGFR). Stone-related variables included stone volume, stone density measured

in Hounsfield Units (HU) on non-contrast computed tomography (CT), stone multiplicity, and anatomical location. Stone volume was calculated using the ellipsoid formula [6]. In addition, anatomical parameters potentially influencing lithotripsy efficiency and pulse modulation transition were evaluated, including lower pole location, infundibulopelvic anatomy, and complex collecting system configurations according to surgeon assessment and preoperative imaging findings.

Outcomes and Efficiency Parameters

The primary efficiency outcomes included:

- Ablation rate (mm^3/s), calculated as stone volume divided by total laser activation time
- Energy efficiency (J/mm^3), calculated as total delivered energy divided by stone volume
- Total laser time
- Total energy delivered during lithotripsy

Retropulsion was subjectively assessed intraoperatively by the operating surgeon using a 5-point Likert-type scale. Stone-free rate (SFR) was defined as the absence of residual fragments greater than 2 mm on postoperative computed tomography performed one month after surgery. Postoperative complications were classified according to the Clavien–Dindo grading system [7]. Surgeon satisfaction regarding fragmentation efficiency and overall intraoperative performance was evaluated using a 10-point visual analog scale (VAS).

Study Focus and Pulse Modulation Transition Analysis

The primary focus of the present study was centered on the subgroup of patients requiring intraoperative transition from M-Ho:YAG pulse modulation to VB pulse modulation (M-Ho:YAG + VB group). Particular emphasis was placed on identifying the preoperative stone-related and anatomical characteristics, as well as intraoperative parameters, that could predict or precede the need for pulse modulation transition during endoscopic lithotripsy.

Statistical analyses were performed using GraphPad Prism version 10. Continuous variables were reported as mean ± standard deviation (SD), while categorical variables were expressed as counts and percentages (n, %). Correlations among clinical and procedural variables were evaluated using Spearman's rank correlation coefficient (r). A two-sided p-value < 0.05 was considered statistically significant.

Results

In this cohort of 400 patients, most were treated with Magneto Mode alone (MG, n = 301), while a smaller proportion received the combined approach with Virtual Basket (MG + VB, n = 99). Pre-operatively, patients showed a mean age of 55.68 years and a mean BMI of 27.09 kg/m^2; renal function (mean

creatinine 1.11 mg/dl; eGFR 80.87 mL/min), and the lithiasis burden (mean stone volume 1804 mm³; 1.29 stones per patient). The anatomical distribution of stones was mainly renal, with the lower pole representing the most frequent location (39%), followed by the upper pole (16.75%) and proximal ureter (14.75%); distal ureter, renal pelvis, and mixed locations accounted for smaller proportions (Table 1).

Table 1
Preoperative features of 400 patients treated with

		Patient Group (n = 400)
Age, Years	**Mean (SD)**	**55.68 (13.42)**
Gender		
Males	n (%)	263 (65.75)
Females	n (%)	137 (34.25)
BMI, Kg/m^2	Mean (SD)	27.09 (4.91)
Stone volume, mm^3	Mean (SD)	1804 (3539)
Hounsfield units	Mean (SD)	938.0 (257.4)
Preoperative Hb, g/dl	Mean (SD)	12.73 (1.50)
Preoperative Cr, mg/dl	Mean (SD)	1.109 (0.35)
eGFR, ml/min	Mean (SD)	80.87 (14.50)
Stone location		
Distal ureter	n (%)	39 (9.75)
Proximal ureter	n (%)	59 (14.75)
Upper pole kidney	n (%)	67 (16.75)
Lower pole kidney	n (%)	156 (39.00)
Bladder	n (%)	3 (0.75)
Renal pelvis	n (%)	37 (9.25)
Mixed locations	n (%)	39 (9.75)
SD Standard Deviation, M males, F females, BMI body mass index, *Hb* haemoglobin, *Cr* creatinine, eGFR estimated Glomerular Filtration Rate		

Intra-operatively, mean laser time was similar between groups (18.69 minutes in M-Ho:YAG + VB vs 19.32 minutes in M-Ho:YAG), whereas differences were observed in total energy delivered (29.30 vs 51.62) and ablation rate (1.31 vs 1.12 mm³/s). Hospitalization time was in both groups within 24 hours (Table 2).

Table 2 - Perioperative outcomes of 400 patients treated with			
		Patient Group (M-Ho YAG) (n = 301)	**Patient Group (M-Ho YAG + VB) (n = 99)**
Laser-on time, min	Mean (SD)	19.32 (13.71)	18.69 (0.65)
Ablation Rate, mm^3/s	Mean (SD)	1.12 (1.36)	1.31 (1.64)
Delivered energy, KJ	Mean (SD)	71.87 (4.15)	46.98 (4.71)
Hospitalization, days	Mean (SD)	24 (14.99)	21.57 (19.02)
Stone location			
Distal ureter	n (%)	30 (7.5)	9 (2.25)
Proximal ureter	n (%)	51 (12.75)	8 (2.0)
Upper pole kidney	n (%)	39 (9.75)	28 (7.0)
Lower pole kidney	n (%)	119 (29.75)	37 (9.25)
Bladder	n (%)	2 (0.5)	1 (0.25)
Renal pelvis	n (%)	29 (7.25)	8 (2.0)
Mixed locations	n (%)	31 (7.75)	8 (2.0)
SD Standard Deviation			

The correlation matrix shows the relationship among clinical and procedural variables. A positive correlation was observed between stone volume and the ranked procedural technique (r = 0.69), as well as between stone volume and total energy delivered (r = 80).

The ranked procedural technique also correlated with total energy (r = 0.59) and hospitalization time (r = 0.41). Hospitalization time showed a weak positive correlation with stone volume (r = 0.09) and total energy (r = 0.11).

Hounsfield Units demonstrated weak correlations with stone volume (r = 0.08=, total energy (r = 0.12), and technique (r = 0.13). ASA score showed minimal correlations with the other variables. VB use and M-Ho:YAG use displayed a perfect inverse correlation (r=-1.00). Retropulsion rank showed a moderate positive correlation with VB use (r = 0.46) and a moderate negative correlation with M-Ho:YAG use (r=-0.45), while correlations with other variables were weak (Fig. 1).

Pulse modulation analysis showed variability in M-Ho:YAG and VB utilization across anatomical locations. The lower pole, representing the most frequent site, displayed high usage percentages for

both modalities. The upper pole and ureteral locations showed heterogeneous distributions of M-Ho:YAG and VB use, with variable percentages across sites. Overall, the figure illustrates that the proportion of M-Ho:YAG and VB use differs according to stone location, with overlapping ranges across anatomical areas.

Table 3 demonstrates a favorable safety profile for the cohort, with a very low incidence of postoperative complications. Only minor adverse events were reported, all classified as Clavien-Dindo grade I–II, confirming the minimally invasive nature of the procedure. Specifically, grade I complications were rare, including limited cases of bleeding related to difficult access (0.75%) and a single ureteral injury (0.25%). Similarly, grade II complications were infrequent and mainly associated with anatomical or technical challenges such as narrow infundibulum and nephroptosis, each occurring in less than 1% of patients. Importantly, no major complications (Clavien ≥ III) were observed, supporting the overall procedural safety. Postoperative renal function remained stable, as indicated by a mean eGFR of 78.41 mL/min, showing only a minimal decline compared to preoperative values. Hemoglobin levels also exhibited a slight decrease (mean 12.20 g/dL postoperatively), which is clinically acceptable and consistent with the low bleeding rates reported. Finally, the SFR at 30 days postoperative was 98.5%.

Table 3
– Postoperative outcomes

		Patient Group (n = 400)
Clavien Dindo I		
Bleeding (Difficult access)	n (%)	3 (0.75)
Ureteral injury	n (%)	1 (0.25)
Clavien Dindo II		
Bleeding (Difficult access)	n (%)	3 (0.75)
Narrow renal infundibulum	n (%)	3 (0.75)
Nephroptosis/Floating kidney (Difficult access)	n (%)	3 (0.75)
eGFR	Mean (SD)	78.41 (13.20)
Hb (post-surgery)	Mean (SD)	12.20 (1.735)

Discussion

Over the last decade, laser lithotripsy has undergone remarkable technological evolution, fundamentally changing the way urinary stones are treated. Advances in laser platforms have progressively shifted the field from simple fragmentation strategies toward more sophisticated dusting approaches, aiming to maximize stone ablation while minimizing retropulsion and improving procedural efficiency. As a result,

modern endourologists now have access to multiple technologies capable of modifying laser–stone interactions according to specific treatment objectives. In parallel with increases in laser power and frequency, several pulse modulation technologies have been introduced to optimize energy transmission through water and improve lithotripsy performance. Systems such as MOSES™, Vapor Tunnel™, and Virtual Basket™ were specifically designed to enhance stone ablation while reducing retropulsion, thereby improving control during ureteroscopic procedures. These innovations highlighted the growing importance of pulse characteristics as a determinant of clinical performance, extending beyond traditional parameters such as energy and frequency [8–9]. A major milestone in this evolution was the introduction of the TFL, which offered a fundamentally different laser architecture and rapidly gained popularity due to its high ablation efficiency, low retropulsion profile, and ability to generate very fine dust particles. The lower peak power associated with TFL technology has been proposed as one of the key factors underlying these advantages, leading to increasing interest in strategies capable of reproducing similar laser behavior within Ho:YAG platforms [10].

More recently, M-Ho:YAG pulse modulation was developed with the aim of combining the well-established safety and versatility of Ho:YAG technology with a lower peak power profile. By substantially extending pulse duration and reducing peak power output, M-Ho:YAG seeks to improve dusting efficiency and stone stabilization while maintaining the advantages of traditional Ho:YAG systems [4]. Early clinical experiences have demonstrated promising outcomes regarding ablation efficacy and retropulsion control, suggesting that this technology may represent an important step in the ongoing refinement of laser lithotripsy [11]. Interestingly, as laser technologies continue to evolve, the focus is gradually shifting from identifying a single superior platform toward understanding how different laser behaviors can be strategically integrated during surgery. In contemporary endourological practice, lithotripsy is increasingly recognized as a dynamic process in which treatment goals may change throughout the procedure. This concept provides the rationale for evaluating not only individual pulse modulation technologies, but also the circumstances under which surgeons transition between them to optimize procedural outcomes.

Several studies have identified stone burden and composition as key determinants of lithotripsy performance. Higher stone density has been associated with longer procedural duration, and both stone volume and mean HU values have been recognized as predictors of operative time [12]. However, evidence specifically evaluating the relationship between stone density and laser efficiency remains limited. Molina et al. demonstrated a positive correlation between laser activation time and both stone volume and density, with a mean stone density approaching 1,000 HU [13]. Beyond operative duration, stone density appears to directly influence the effectiveness of different pulse modulation technologies. Rico et al. reported that Vapor Tunnel™, a long-pulse Ho modality characterized by minimal peak power delivery, exhibited a significant reduction in both lithotripsy efficacy and efficiency as stone density increased [14]. These findings suggest that low peak-power pulse profiles may be less effective when treating harder calculi. In contrast, higher-density stones may require pulse modulation technologies capable of generating greater peak power and distinct vapor bubble dynamics to optimize energy transmission and fragmentation efficiency. The results of the present study further support this concept.

Stone density emerged as an independent predictor of intraoperative conversion from M-Ho:YAG to VB mode. Collectively, these findings highlight the importance of tailoring pulse modulation strategies according to stone characteristics rather than relying on a single lithotripsy setting throughout the procedure.

Stone volume and anatomical location are among the most important factors influencing procedural complexity during endoscopic lithotripsy. As stone burden increases or access becomes more challenging, modifications in laser settings or pulse modulation strategies may be required to optimize ablation performance and maximize stone-free outcomes. Consequently, lithotripsy should be viewed as a dynamic process in which treatment parameters are continuously adapted according to intraoperative findings. Gauhar et al. demonstrated that dusting is generally preferred for smaller stones, favorable anatomical locations, and lower stone densities. In contrast, popcorning is more frequently employed for larger calculi, multiple stones, or stones located in the lower pole [15]. This technique typically utilizes pulse-modulated or continuous-pulse laser settings at high frequencies, facilitating rapid fragmentation and accelerating stone clearance [16]. Such an approach may be particularly advantageous in gravity-dependent calyces, where the evacuation of fine debris is often more challenging and where fragmentation strategies can improve overall procedural efficiency. Stone location remains a critical determinant of lithotripsy strategy, frequently requiring different energy delivery profiles to overcome anatomical limitations [17]. In the present study, lower pole stones were independently associated with the need for intraoperative conversion from M-Ho:YAG to VB mode. This finding suggests that anatomical constraints, together with stone burden and density, may necessitate more aggressive pulse modulation profiles to maintain efficient fragmentation and stone clearance. However, in a recent study, Shrestha et al. demonstrated excellent outcomes using FANS for lower pole stones achieving a SFR of 98.4% regardless of sheath size [18].

The safety of TFL has been consistently demonstrated across multiple studies, showing a low incidence of adverse events and a limited likelihood of thermal injury when adequate irrigation is provided. Owing to its greater absorption by water, TFL allows effective energy delivery to tissues while maintaining a shallow depth of penetration, facilitating accurate coagulation and controlled tissue effects with minimal carbonization [19]. Given the close resemblance between the physical and laser characteristics of M-Ho:YAG and TFL, a comparable safety performance can be anticipated. This observation was supported by our findings, as neither treatment group experienced significant intraoperative complications, and no clinically relevant bleeding events were observed.

This study has several limitations that should be acknowledged. First, its multicenter design inherently introduces operator-related bias, as surgical decision-making, perioperative management, and technical preferences may vary among participating centers. Differences in surgical strategies, endoscopic equipment, access sheath utilization, and stone treatment techniques were left to the discretion of individual surgeons, potentially influencing both efficacy and safety outcomes. However, these variations also reflect contemporary real-world clinical practice and therefore enhance the external validity of our findings.

Second, despite efforts to standardize data collection and outcome assessment across centers, procedural heterogeneity may have affected the final results. Variations in surgical experience, case selection, and postoperative management protocols represent potential confounding factors that cannot be completely controlled in a multicenter analysis. Finally, to ensure a homogeneous assessment of stone-free status across all participating institutions, SFR was defined as the absence of residual fragments > 2 mm. Although complete absence of residual fragments is increasingly considered the ideal endpoint after endourological procedures, the use of a > 2 mm threshold was selected to facilitate consistent reporting and comparison among centers. Consequently, the reported SFR may differ from studies adopting stricter definitions of complete stone clearance.

Conclusion

Large stone burden, lower pole location, and higher stone density were identified as the principal factors associated with the need for intraoperative transition from M-Ho:YAG to VB pulse modulation. These findings suggest that lithotripsy performance may be enhanced through a flexible and individualized pulse modulation strategy adapted to specific stone characteristics rather than relying on a single fragmentation approach throughout the procedure. Further prospective studies with larger patient cohorts and randomized designs are warranted to validate these preliminary findings and better define the optimal indications for dynamic pulse modulation during Ho:YAG laser lithotripsy.

Abbreviations

Ho:YAG = Holmium:Yttrium-Aluminum-Garnet

TFL = thulium fiber laser

RIRS = retrograde intrarenal surgery

BMI = body mass index

SD = standard deviation

HU = Hounsfield Units

SFR = stone-free Rate

M-Ho:YAG: Magneto Holmium:Yttrium-Aluminum-Garnet

VB: Virtual Basket

ASA = American Society of Anesthesiologists

eGFR = estimated glomerular filtration rate

VAS = visual analog scale

Declarations

Authors' contribution LR: manuscript writing and editing. LR, DP, MRS, AK, JV: data analysis and data management.

LR, GB, FGS and PC: project development.

Funding: None

Conflict of Interest: Luis Rico certifies that all conflicts of interest,

including specific financial interests and relationships and affiliations relevant

to the subject matter or materials discussed in the manuscript (eg,

employment/affiliation, grants or funding, consultancies, honoraria, stock

ownership or options, expert testimony, royalties, or patents filed,

received, or pending), are the following: The authors have no conflicts of interest to

declare.

Human Ethics and Consent to Participate declarations: not applicable

Informed consent: I hereby confirm that all participants included in this study were duly informed about the nature and purpose of the research and provided their informed consent for the use of their clinical, imaging, and procedural data for scientific and academic purposes. All data were collected and analyzed in accordance with applicable ethical standards and institutional regulations. Patient confidentiality and anonymity have been strictly maintained throughout the study, and no identifying personal information is disclosed in this manuscript. The study was conducted in compliance with the principles outlined in the Declaration of Helsinki and relevant local ethical requirements.

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Figures

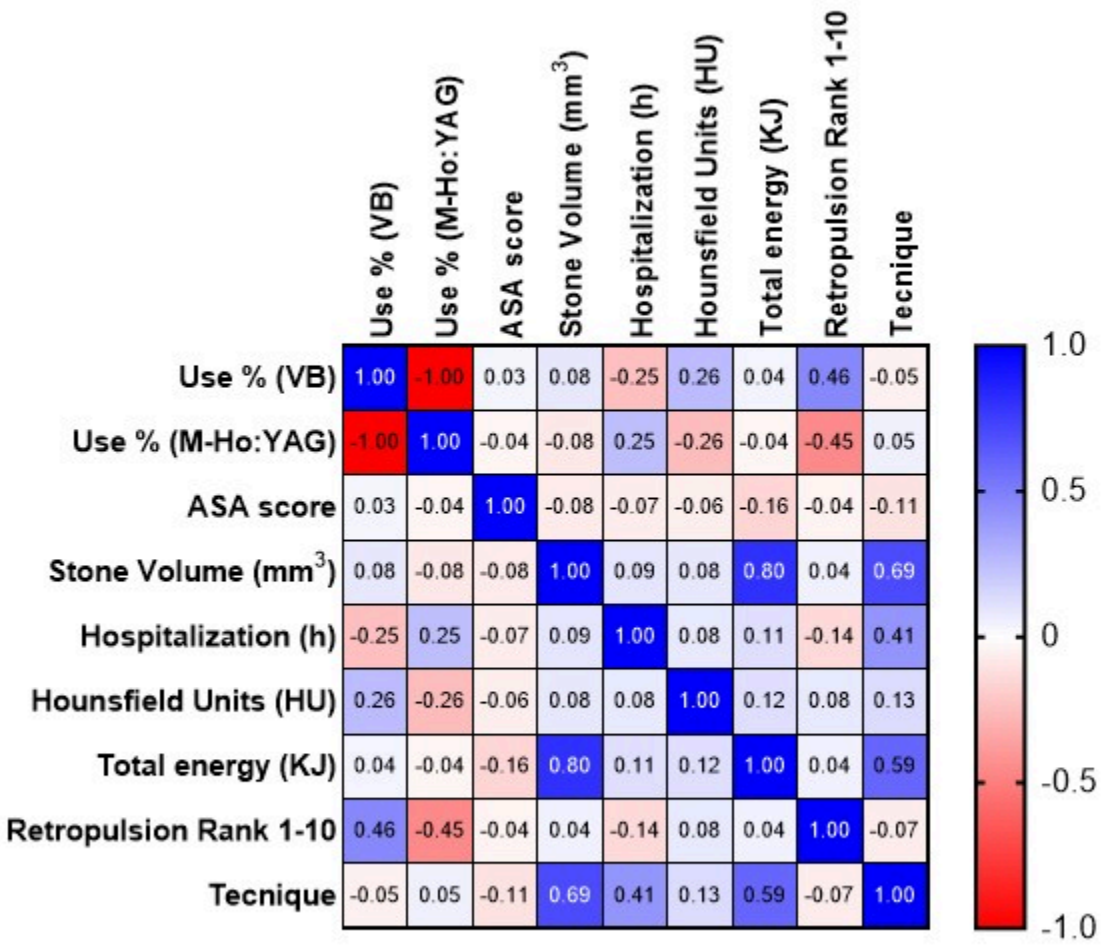


Figure 1

Correlation matrix of the main clinical and procedural variables: colors indicate the strength and direction of correlations (blue = positive, red = negative). A strong positive correlation is observed between stone volume and total energy delivered (r = 0.80), as well as between stone volume and technique (r = 0.69). VB use shows a perfect inverse correlation with M-Ho:YAG (r = −1.00). Other associations are weak to moderate.

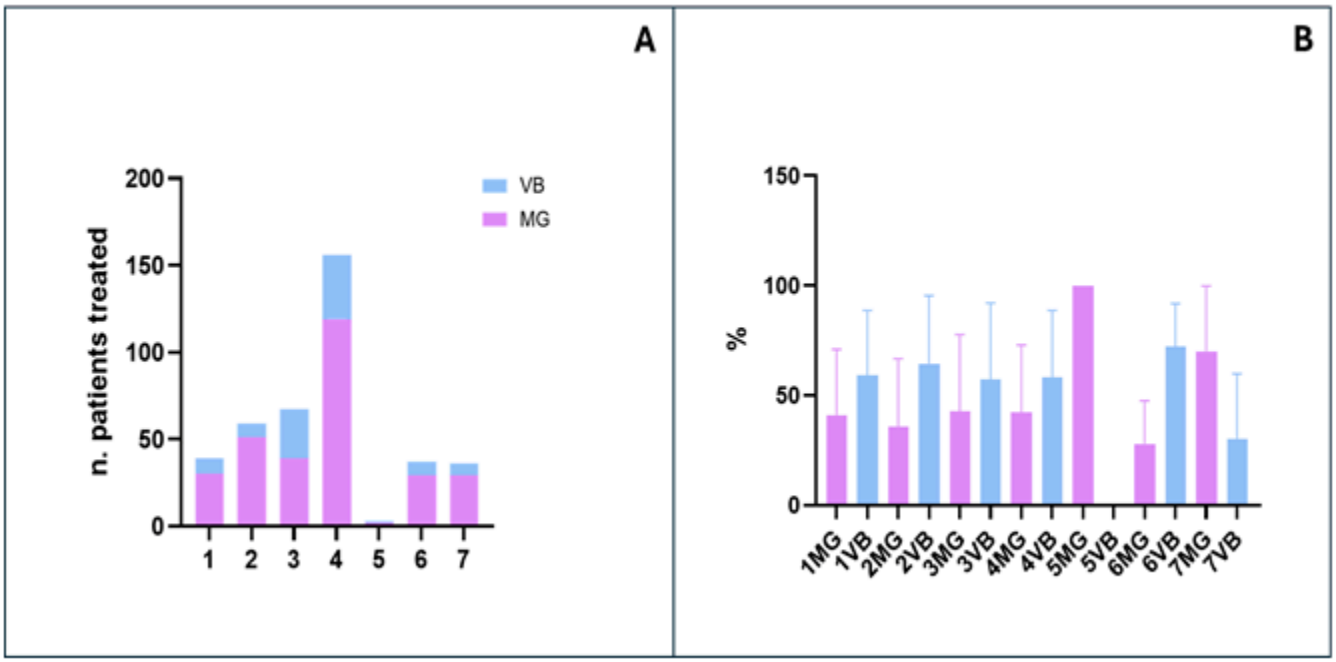


Figure 2

(A) Number of patients treated according to stone location and laser modality, using Magneto (MG) alone or requiring additional Virtual Basket (VB) support. (B) Percentage use of MG versus VB according to stone location, calculated in the subpopulation of patients in whom a switch to VB was required. Stone locations are coded as follows: 1 = distal ureter, 2 = proximal ureter, 3 = upper pole kidney, 4 = lower pole kidney, 5 = bladder, 6 = renal pelvis, 7 = mixed locations.