



Review – Stone Disease

Laser Ablation Efficiency, Laser Ablation Speed, and Laser Energy Consumption During Lithotripsy: What Are They and How Are They Defined? A Systematic Review and Proposal for a Standardized Terminology

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Abstract

Context: Laser performance for lithotripsy is currently reported using units of measurement such as J/mm³, mm³/J, mm³/s, s/mm³, and mm³/min. However, there are no current standardized definitions or terminology for these metrics. This may lead to confusion when assessing and comparing different laser systems.

Objective: The primary objective was to summarize outcome values and corresponding terminology from studies on laser lithotripsy performance using stone volume in relation to time or energy. The secondary objective was to propose a standardized terminology for reporting laser performance metrics.

Evidence acquisition: A systematic review of the literature was conducted using the search string (“j*/mm3” OR “mm3/j*” OR “mm3/s*” OR “s*/mm3” OR “mm3/min*” OR “min*/mm3” AND “lithotripsy”) on Scopus, Web of Science, Embase, and PubMed databases. Study selection, data extraction, and quality assessment were performed independently by two authors.

Evidence synthesis: A total of 28 studies were included, covering holmium:yttrium-aluminum-garnet (Ho:YAG), MOSES, and thulium fiber laser (TFL) technologies. Laser energy consumption values reported for the studies ranged from 2.0 – 43.5 J/mm³

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in vitro and from 2.7 – 47.8 J/mm³ *in vivo*, translating to laser ablation efficiency of 0.023 – 0.500 mm³/J and 0.021 – 0.370 mm³/J, respectively. Laser ablation speeds ranged from 0.3 – 8.5 mm³/s *in vivo*, translating to lasing time consumption of 0.12 – 3.33 s/mm³. Laser efficacy ranged from 4.35 – 51.7 mm³/min *in vivo*. There was high heterogeneity for the terminology used to describe laser performance for the same metrics.

Conclusions: The range of laser performance metric values relating stone volume to energy or time is wide, with corresponding differing terminology. We propose a standardized terminology for future studies on laser lithotripsy, including laser ablation efficiency (mm³/J), laser ablation speed (mm³/s), and laser energy consumption (J/mm³). Laser efficacy (mm³/min) is proposed as a broader term that is based on the total operative time, encompassing the whole technique using the laser.

Patient summary: We reviewed studies to identify the units and terms used for laser performance when treating urinary stones. The review revealed a wide range of differing units, outcomes, and terms. Therefore, we propose a standardized terminology for future studies on laser stone treatment.

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1. Introduction

Treatment of urinary stone disease has been increasing worldwide [1]. Among the tools used to treat urinary stone disease, the laser has become the mainstay for lithotripsy in endourology [2]. There has been an evolution in laser technology, from the established holmium:yttrium-aluminum-garnet (Ho:YAG) laser and pulse modulation to thulium fiber laser (TFL), and the more recent novel pulsed thulium:YAG (p-Tm:YAG) laser [3–5].

Assessment of clinical stone burden has shifted to include volume measurements [6], mainly because of limitations in measuring the diameter for stones of differing shapes [7]. Assessment of laser ablation performance has also incorporated stone volume in terms of Joules/mm³ in addition to mm³/s as proxies for laser performance [8]. However, to the best of our knowledge, there is no standardized terminology for reporting laser ablation performance metrics in relation to volume, energy, and time.

The aim of our study was to review laser ablation performance outcomes in lithotripsy studies and the terminology in relating stone volume to laser energy and time. We also propose a standardized terminology for reporting laser performance parameters.

2. Evidence acquisition

This study was conducted in accordance with the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) checklist [9].

2.1. Search strategy

A systematic review of the literature was carried out on June 26, 2023 using the Scopus, Web of Science, Embase, and PubMed databases, with no time-period restriction. The search string (“j*/mm3” OR “mm3/j*” OR “mm3/s*” OR “s*/mm3” OR “mm3/min*” OR “min*/mm3” AND “lithotripsy”) was used for articles in English. Reference lists for the manuscripts selected were checked manually for additional eligible articles.

2.2. Inclusion and exclusion criteria

The inclusion criteria were as follows: (1) reports on laser ablation performance in J/mm³, mm³/J, mm³/s, s/mm³, mm³/min, or min/mm³; and (2) evaluations of current laser technologies (Ho:YAG, TFL or p-Tm:YAG). Original studies and conference abstracts on both *in vitro* and *in vivo* studies were considered. Systematic reviews, case reports, editorials, and letters were not considered. The exclusion criteria were as follows: (1) studies not related to human laser lithotripsy or models; (2) comparative studies using non-laser-related comparators; and (3) ambiguous reporting of results, typically studies reporting results in mm³/s but not specifying which time period the denominator referred to. If either total operative time or lasing time was reported, it was assumed that the denominator in mm³/s referred to the time value reported, and these studies were not excluded.

2.3. Outcomes

The primary outcome of interest was laser performance reported in units of J/mm³, mm³/J, mm³/s, s/mm³, mm³/min, or min/mm³. The values reported were interpreted according to the following definitions: laser energy consumption = energy consumed per unit of ablated stone volume (J/mm³); laser ablation efficiency = ablated stone volume per unit of energy (mm³/J); laser ablation speed = ablated stone volume per unit of lasing time (mm³/s); lasing time consumption = lasing time per unit of ablated stone volume (s/mm³); and laser efficacy = ablated stone volume per unit of operative time (mm³/min). Lasing time was defined as the cumulative time of laser pedal activation.

2.4. Data extraction

Two authors (J.-L.K. and E.X.K.) extracted data independently using a standardized form. Conflicts were resolved via selective analysis and consensus. The studies included were assessed for characteristics and relevant outcomes and are listed in Tables 1–3. When only results expressed

Table 1 – Summary of *in vitro* studies: main characteristics and results

| Study | Laser type | Fiber size (µm) | Study setup | Stone volume and/or density | Ablation volume measurement method | Target | Comparator groups | Laser energy consumption (J/mm ³) ^b | Laser ablation efficiency (mm ³ /J) ^b | Laser ablation speed (mm ³ /s) |
|--------------------|----------------------|-----------------|--|-----------------------------|--|-----------|----------------------|--|---|---|
| Panthier 2020 [12] | Ho:YAG 30 W | 272 | Single pulse | Not specified | Micro-CT with 3D segmentation software | COM | 0.6 J | 34.0 (3.3) | 0.029 (0.003) ^c | – |
| | | | | | | | 0.8 J | 23.2 (5.2) | 0.043 (0.008) ^c | |
| | | | | | | | 1.0 J | 14.7 (3.9) | 0.068 (0.014) ^c | |
| | | | | | | CYS | 0.6 J | 8.5 (1.8) | 0.118 (0.021) ^c | |
| | | | | | | | 0.8 J | 7.8 (5.8) | 0.128 (0.055) ^c | |
| | | | | | | UA | 1.0 J | 6.4 (2.2) | 0.156 (0.040) ^c | |
| | | | | | | | 0.6 J | 3.2 (0.6) | 0.313 (0.049) ^c | |
| | | | | | | | 0.8 J | 2.4 (0.7) | 0.417 (0.094) ^c | |
| | | | | | | | 1.0 J | 2.0 (0.5) | 0.500 (0.094) ^c | |
| King 2022 [13] | Ho: YAG ^a | 200 | 10 pulses at 10 different surface points | Not specified | Optical coherence tomography | BegoStone | Annular beam, 1.0 J | 15.4 (2.6) ^c | 0.065 (0.013) | – |
| | | | | | | | Circular beam, 1.0 J | 43.5 (5.0) ^c | 0.023 (0.003) | |

CT = computed tomography; 3D = three-dimensional; COM = calcium oxalate monohydrate; CYS= cystine; UA = uric acid.
^a Power not reported.
^b Reported as mean (standard deviation).
^c Calculated for this review.

as either J/mm³ or mm³/J were reported, we calculated the value for the corresponding unreported term (1/[mm³/J] = [J/mm³]). This was also done for mm³/s and s/mm³ results in the same manner. When the laser ablation speed was reported in minutes, this was converted to seconds to maintain consistency.

2.5. Quality assessment: risk of bias

For applicable studies, two authors (J.-L.K. and E.X.K.) assessed the risk of bias independently using two Cochrane tools: RoB 2 [10] for randomized control trials, and ROBINS-I [11] for comparative studies. Conflicts were resolved via consensus. A comprehensive description of the risk-of-bias assessment can be found in the [Supplementary material](#).

Considering the heterogeneity of the study outcomes, a narrative review was performed rather than a quantitative analysis. The structure of the manuscript was decided via consensus among the authors.

3. Evidence synthesis

3.1. Literature search

We identified 96 studies via the database searches and two additional studies from reference lists, of which 28 studies were selected for final review [8,12–38]. The selection process is detailed in [Figure 1](#). There were two *in vitro* [12,13] and 26 *in vivo* studies [8,14–38]. Nine were peer-reviewed conference abstracts [13,16,19,22,29–31,36,37] and the rest were full-text peer-reviewed original studies.

3.2. Quality assessment: risk of bias

Risk-of-bias assessment was not applicable to the two *in vitro* studies or to ten self-controlled observational series. Of the sixteen remaining studies, only one had high risk of bias [36], with all other studies having moderate risk of bias ([Supplementary Fig. 1](#)).

3.3. Study characteristics and results

Both of the *in vitro* studies used methods relating to single pulse(s) on the stone surface and calculated the ablated stone crater volume ([Table 1](#)). One reported laser energy consumption (J/mm³) [12] and the other laser ablation efficiency (mm³/J) [13]. Neither reported time-related outcomes.

Characteristics of the 26 *in vivo* studies are summarized in [Table 2](#). Three (12%) were randomized controlled trials [14,17,36], five (19%) were prospective comparative studies [18,20,24,27,38], ten (38%) were prospective observational studies [8,15,16,25,26,28,29,32,34,35], and eight (31%) were retrospective studies [19,21–23,28,30,31,37]. The number of patients included in the studies ranged from 26 to 631. Surgery types included mostly ureteroscopy (ureter and kidney), with six studies (23%) evaluating mini percutaneous nephrolithotomy (mPCNL) [22,27,28,30,35,38]. Methods for measuring stone volume included preoperative computed tomography (CT) software calculations in six studies (23%) [8,15,16,34,35,38] and the CT ellipsoid formula in twelve studies (46%) [14,17,18,20,23–28,32,33]. One study included the use of either CT or X-ray imaging

Table 2 – Summary of in vivo studies: characteristics

| Study | Design | Pts | Laser type | Comparator groups | Surgery | Stone location | Laser fiber (µm) | Method for measuring ablated stone volume | Definition of SF status | Method for measuring SFR | SFR assessment | Basketing/ Sheath evacuation allowed |
|---|--------|-----|----------------------------|-------------------|-----------------|----------------|--------------------------|---|---|---|------------------|--------------------------------------|
| Regular Ho:YAG | | | | | | | | | | | | |
| Alghamdi 2020 [14] | RCT | 145 | Ho:YAG 30 W | Pulse shape | URS | K & U | 275, 600 | Preop CT, EF | No fragments ≥1 mm | Intraoperative | Intraoperatively | NS |
| Panthier 2021 [15] | PO | 26 | Ho:YAG 30 W & 100 W | – | URS | K | 230, 272 | Preop CT, imaging software ^b | No fragments >3 mm on CT or endoscopic absence of fragments | CT, endoscopic inspection at end of procedure | NS | NS |
| Ventimiglia 2021 [8] | PO | 30 | Ho:YAG 35 W | – | URS | K | 272 | Preop CT, 3D-RV | NS | CT | 4 wk | NS |
| Panthier 2022 [16] | PO | 45 | Ho:YAG ^a | – | URS | K | Not specified | Preop CT, imaging software ^b | NS | NS | NS | Yes |
| Shrestha 2022 [17] | RCT | 120 | Ho:YAG 120 W | Settings | URS | K | 200 | Preop CT, EF | No fragments | X-Ray KUB and US | 4 wk | NS |
| Ho:YAG MOSES technology | | | | | | | | | | | | |
| Majdalany 2021 [18] | PC | 29 | MOSES 120 W 1.0 vs 2.0 | Laser | URS | K | 230 | Preop CT, EF | No fragments | X-Ray KUB, US, or CT | NS | Yes (stone analysis) |
| Antoine 2022 [19] | R | 82 | MOSES 120 W 1.0 vs 2.0 | Laser | URS | K & U | 200 | NS | NS | Intraoperative | Intraoperatively | NS |
| Ho:YAG MOSES technology vs regular Ho:YAG | | | | | | | | | | | | |
| Mullerad 2017 [20] | PC | 34 | MOSES 120 W | Laser mode | URS | K & U | 200, 365, 550 | Preop CT, EF | NR | NA | NA | NS |
| Mekayten 2019 [21] | R | 631 | MOSES 120 W vs Ho:YAG 20 W | Laser | URS | K & U | 200, 365, 550 | NS | <2–3 mm and asymptomatic | CT or US + X-ray KUB | 4–6 wk | NS |
| Dunne 2021 [22] | R | 140 | MOSES 120 W vs Ho:YAG | Laser | mPCNL | K & U | Not specified | Preop CT, exact method NS | NS | NS | NS | Yes |
| Wang 2021 [23] | R | 216 | MOSES 120 W | Laser mode | URS | K | 200 | Preop CT, EF | No fragments ≥2 mm | X-Ray KUB or US | 4 wk | No |
| TFL | | | | | | | | | | | | |
| Enikeev 2020 [24] | PC | 40 | TFL | Settings | URS | K | Not specified | Preop CT, EF | No stones >2mm | CT | 3 mo | NS |
| Corrales 2021 [25] | PO | 50 | TFL | Stone location | URS | K & U | 150, 200 | Preop CT, EF | NR | NA | NA | No (implied) |
| Enikeev 2021 [26] | PO | 149 | TFL | – | URS | U | 200, 400 | Preop CT, EF | No fragments >2 mm | CT | 3 mo | NS |
| Korolev 2021 [27] | PC | 125 | TFL | Settings | mPCNL | K | 400 | Preop CT, EF | No fragments ≥2 mm | CT | 3 mo | Yes |
| Taratkin 2021 [28] | R | 318 | TFL | Surgery | URS & mPCNL | K | 200 (URS) 400 (mPCNL) | Preop CT, EF | No fragments | Low-dose CT, US | 3 mo | NS |
| Vaddi 2021 [29] | PO | 109 | TFL | – | URS | K | NS | Preop CT, exact method NS | NS | CT | 3 mo | NS |
| Batra 2022 [30] | R | 88 | TFL | Surgery | URS & mPCNL | K | NS | NS | NS | CT, X-ray KUB | POD1, 1 mo | NS |
| Corrales 2022 [31] | R | 81 | TFL | Laser | URS | K | 150 | NS | NR | NA | NA | NS |
| Sierra 2022 [32] | PO | 50 | TFL | – | URS | K & U | 150, 200 | Preop CT and X-ray, EF | No fragments >150 µm core diameter laser fiber | End of procedure ^c | Intraoperatively | No |
| Taratkin 2022 [33] | PO | 153 | TFL | HU | URS | K | 200, 400 | Preop CT, EF | No fragments >2 mm | CT | 3 mo | NS |
| Vaddi 2022 [34] | PO | 126 | TFL | – | URS | K & U | 200 | Preop CT, imaging software | No stones >2 mm | CT | 3 mo | No |
| Shah 2020 [35] | PO | 54 | TFL | – | mPCNL + suction | K | 400 | Preop CT, imaging software | NS | CT, X-ray KUB | 48 h, 1 mo | Yes |
| TFL vs regular Ho:YAG or Ho:YAG MOSES technology | | | | | | | | | | | | |
| Ghazi 2021 [36] | RCT | 62 | TFL vs Ho:YAG 100 W | Settings | URS | K | NS | NS | NS | CT | 1 mo | NS |
| Edison 2022 [37] | R | 355 | TFL vs Ho:YAG ^a | Laser | URS | K & U | NS | Imaging modality NS, EF | NR | NA | NA | Yes |

Table 2 (continued)

| Study | Design | Pts | Laser type | Comparator groups | Surgery | Stone location | Laser fiber (µm) | Method for measuring ablated stone volume | Definition of SF status | Method for measuring SFR | SFR assessment | Basketing/Sheath evacuation allowed |
|-----------------|--------|-----|--------------------|-------------------|-----------------|----------------|--------------------------|---|--------------------------------|--------------------------|----------------|-------------------------------------|
| Patil 2022 [38] | PC | 102 | TFL vs MOSES 120 W | Laser | mPCNL + suction | K | 365 (MOSES) 400 (TFL) | Preop CT, imaging software | Preop CT, imaging No fragments | CT | 48 h, 1 mo | Yes |

Pts = patients; SF = stone-free; SFR = stone-free rate; RCT = randomized controlled trial; PO = prospective observational study; PC = retrospective comparative study; R = retrospective comparative study; URS = ureteroscopy (covering both ureteral and kidney stones); mPCNL = mini-percutaneous nephrolithotomy; K = kidney; U = ureter; Preop = preoperative; CT = computed tomography; EF = ellipsoid formula; 3D-RV = three-dimensional reconstructed volume; NS = not specified; NR = not reported; NA = not applicable; KUB = kidney-ureter-bladder; US = ultrasound; TFL = thulium fiber laser; POD1 = postoperative day 1.

a Power not reported.

b "Kidney Stone Calculator" software.

c Fluoroscopically and endoscopically.

for preoperative measurement of stone volume [32]. Definitions, diagnostic methods, and time points for assessment of the stone-free rate were very heterogeneous, as summarized in Table 2.

Results from the 26 *in vivo* studies are summarized in Table 3. Four studies (15%) [14,22,30,37] did not specify mean Hounsfield units. Two (8%) specified the distribution of stone composition types [14,18]. The stone-free rate was not available in five studies (19%) [8,20,25,31,37]. One study reported total laser energy results with a thousand-fold factor higher than what could be expected [36]. We assume that the authors mistakenly labeled energy in kilojoules instead of joules, and thus we interpreted the values as being in joules. The operative time was missing in 12 studies (46%) [19,20,24–26,28–33,36] and the lasing time was not reported in four studies (15%) [8,16,22,37]. Laser energy consumption (J/mm³) was not available in seven studies (27%) [14,20,22,23,30,35,37]. Of note, none of the *in vivo* studies reported laser ablation efficiency (mm³/J). Laser ablation speed (mm³/s) was not available in four studies (15%) [14,16,21,37], of which one had ambiguity regarding the definition of the time unit [16] and one presented results as lasing time consumption (s/mm³) instead [21]. Two studies (8%) reported laser efficacy (mm³/min) [14,37].

3.4. Outcomes

Laser energy consumption ranged from 2.0 – 43.5 J/mm³ in the *in vitro* Ho:YAG studies. For the *in vivo* studies, laser energy consumption ranged from 9.7 – 27.9 J/mm³ for regular Ho:YAG laser, from 9.0 – 47.8 J/mm³ for Ho:YAG MOSES technology, and from 2.7 – 21.2 J/mm³ for TFL.

Laser ablation efficiency ranged from 0.023 – 0.500 mm³/J in the *in vitro* Ho:YAG studies. For *in vivo* studies, laser ablation efficiency ranged from 0.036 – 0.103 mm³/J for regular Ho:YAG laser, from 0.021 – 0.111 mm³/J for Ho:YAG MOSES technology, and from 0.047 – 0.370 mm³/J for TFL.

Among the *in vivo* studies, the laser ablation speed ranged from 0.4 – 4.1 mm³/s for regular Ho:YAG laser, from 0.66 – 4.76 mm³/s for Ho:YAG MOSES technology, and from 0.30 – 8.50 mm³/s for TFL.

Among the *in vivo* studies, lasing time consumption ranged from 0.24 – 2.50 s/mm³ regular Ho:YAG laser, from 0.21 – 1.52 s/mm³ for Ho:YAG MOSES technology, and from 0.12 – 3.33 s/mm³ for TFL.

Laser efficacy in the *in vivo* studies ranged from 4.35 – 51.7 mm³/min for regular Ho:YAG laser, and one study reported 7.1 mm³/min for TFL.

3.5. Discussion

Our review reveals a wide range of laser lithotripsy performance outcomes reported for the ablated volume in relation to energy and time metrics. There was high heterogeneity for the study methodologies applied both *in vitro* and *in vivo*. The studies cover multiple comparators and lithotripsy parameters: various laser technologies (high- and low-power Ho:YAG, MOSES technology, and TFL), a very broad range of laser settings, different stone locations (kidney and ureteric stones), and different surgical approaches (ureteroscopy and PCNL).

Table 3 – Summary of in vivo studies: results

| Study | Comparator (if any) and settings | Stone density (HU) | SFR (%) | Total energy (kJ) | Stone volume (mm ³) | Operative time (min) | Lasings time (s) | Laser energy consumption (J/mm ³) | Laser ablation efficiency (mm ³ /J) | Laser ablation speed (mm ³ /s) | Lasting time consumption (s/mm ³) | Laser efficacy (mm ³ /min) |
|--|---|-------------------------|-----------------|-------------------------------|---------------------------------|--------------------------------|---------------------------|---|--|---|---|---------------------------------------|
| Regular Ho:YAG | | | | | | | | | | | | |
| Alghamdi 2020 [14] | Standard PS (K): 1.5 J x10 Hz | - | 82 | - | 348 (298) ^a | 21.7 (17.2) ^a | 1146 (1263) ^a | - | - | - | - | 22.4 (24.2) ^a |
| | New PS (K): 1.5 J x10 Hz | - | 84 | - | 525 (429) ^a | 17.9 (18.7) ^a | 91.6 (130.5) ^a | - | - | - | - | 51.7 (61.3) ^a |
| | Standard PS (U): 1.5 J x 10 Hz | - | 87 | - | 133 (95) ^a | 10.6 (12.0) ^a | 41.7 (63.7) ^a | - | - | - | - | 28.8 (30.2) ^a |
| | New PS (U): 1.5 J x 10 Hz | - | 83 | - | 197 (139) ^a | 9.3 (9.9) ^a | 40.0 (30.4) ^a | - | - | - | - | 39.9 (44.9) ^a |
| | | | | | | | | | | | | |
| Panther 2021 [15] | 0.5–0.8 J x 15–30 Hz: | 158 <1000: | 81 | 7.9 ^a | 479 | 70 | 1110 | 17.6 | 0.057 | 0.4 | 2.5 | - |
| | 1–1.5 J x 10–15 Hz | 858 >1000 | - | - | (268–4517) ^b | (60–82) ^b | (582–1783) ^b | (13.6–24.7) ^b | (0.040–0.074) ^b | (0.32–0.56) ^b | (1.79–3.09) ^b | - |
| | | 1040 | - | 37.1 | 1599 | 68 | - | 19.0 | 0.053 | 0.7 | 1.43 | - |
| | | (753–1275) ^b | - | (13.3–37.7) ^b | (630–3502) ^b | (36–88) ^b (LT) | - | (14.0–24.0) ^b | (0.042–0.071) ^b | (0.4–0.9) ^b | (1.11–2.50) ^b | - |
| Panther 2022 [16] | Settings NS | 694 <1000: | 79 | NR | 508 | 68 | - | 16.8 ^a | 0.060 ^a | - | - | - |
| | | 314 >1000 | - | - | (225–947) ^b | - | - | - | - | - | - | - |
| Shrestha 2022 [17] | Low power settings: 0.5–0.8 J x 15–20 Hz; 1 J x 10 Hz; 1.2–1.5 J x 15–20 Hz | 1000 | 91 | 4.5 | 372 | 38 | 555 | 9.7 | 0.103 | 0.8 | 1.25 | - |
| | High power settings: 0.2–0.3 J x 60–80 Hz; 1 J x 10 Hz; 0.5 J x 50–80 Hz | 700–1112) ^b | 88 | (2.0–8.5) ^b | (352–688) ^b | (19–60) ^b | (321–780) ^b | (5.3–17.7) ^b | (0.056–0.188) ^b | (0.5–1.3) ^b | (0.77–2.00) ^b | - |
| | 80 Hz | 1012 | - | 9.1 | 368 | 40 | 661 | 27.9 | 0.036 | 0.6 | 1.67 | - |
| Ho:YAG MOSES technology | | | | | | | | | | | | |
| Majumdar 2021 [18] | MOSES 1.0: 0.2–0.3 J x 50–120 Hz; 0.5 J x 50–80 Hz | 784 (369) ^a | 71 | 6.4 (3.1) ^a | 242 (215) ^a | 10.4 (4.5) ^a (LT) | 318 (186) ^a | 32.4 (18.0) ^a | 0.031 (0.011) ^a | 0.88 (0.71) ^a | 1.14 (0.51) ^a | - |
| | MOSES 2.0: 0.2–0.3 J x 90–120 Hz; 0.5 J x 50–80 Hz | 865 (433) ^a | 90 | 12.4 (13.0) ^a | 368 (468) ^a | 14.3 (6.4) ^a (LT) | 420 (408) ^a | 47.8 (60.0) ^a | 0.021 (0.012) ^a | 0.97 (0.51) ^a | 1.03 (0.36) ^a | - |
| | MOSES 1.0: settings NS | 910 ^a | 81 | 4.4 ^a | 315 ^a | - | 275 ^a | 11.0 ^a | 0.091 ^a | 4.76 ^a | 0.21 ^a | - |
| Antone 2022 [19] | MOSES 2.0: settings NS | 845 ^a | 88 | 4.2 ^a | 331 ^a | - | 394 ^a | 21.0 ^a | 0.048 ^a | 1.35 ^a | 0.74 ^a | - |
| | | | | | | | (9–2009) ^a | | | | | |
| Ho:YAG MOSES technology vs regular Ho:YAG | | | | | | | | | | | | |
| Mullerrad 2017 [20] | Lumens 120H MOSES mode: settings NS | 902 | - | 4.5 | 782 | - | 360 | - | - | 1.60 | 0.63 | - |
| | Lumens 120H regular mode: settings NS | (554–1085) ^b | - | (1.6–16.0) ^b | (181–1691) ^b | - | (168–780) ^b | - | - | (0.86–2.96) ^b | (0.34–1.17) ^b | - |
| Mekeyten 2019 [21] | MOSES: 0.7 J (0.16) x 14 Hz (4) ^a | 1085 ^a | 87 | 4.7 (5.0) ^a | 428 ^a | 31.8 ^a | 397.1 ^a | 17.2 (20.1) ^a | 0.058 (0.031) ^a | 0.66 ^a | 1.51 ^a | - |
| | Ho:YAG: 0.5 J (0.12) x 63 Hz (24) ^a | 1021 ^a | 85 | 3.6 (4.1) ^a | 367 ^a | 21.1 ^a | 195.0 ^a | 13.0 (11.9) ^a | 0.077 (0.037) ^a | 1.25 ^a | 0.80 ^a | - |
| Dunne 2021 [22] | MOSES: settings NS | - | 95 ^a | - | - | - | - | - | - | 2.4 ^a | 0.42 ^a | - |
| | Ho:YAG: settings NS | - | - | - | - | 88.1 ^a | - | - | - | 1.8 ^a | 0.56 ^a | - |
| Wang 2021 [23] | Lumens 120H MOSES: contact mode: 0.3 J x 60 Hz | 990 (150) ^a | 87 | - | 674 (41) ^a | 18.4 (5.1) ^a | 299 (64) ^a | - | - | 2.30 | 0.44 | - |
| | Lumens 120H regular DM: 0.3 J x 60 Hz | 994 (150) ^a | 85 | - | 683 (39) ^a | 21.2 (6.8) ^a | 356 (58) ^a | - | - | (2.73–1.91) ^b | (0.52–0.37) ^b | - |
| TFL | | | | | | | | | | | | |
| Einkew 2020 [24] | Laser settings: 0.5 J x 30 Hz | 857 (348) ^a | 93 ^a | 5.6 | 883 | - | 219 | 2.7 | 0.370 | 5.5 | 0.18 | - |
| | Laser settings: 0.15 J x 200 Hz | 894 (407) ^a | - | (1.4–6.4) ^b | (696–1664) ^{b,d} | - | (90–330) ^b | (1.8–9.8) ^b | (0.102–0.556) ^b | (1.5–8.7) ^b | (0.11–0.67) ^b | - |
| Corrales 2021 [25] | U: 0.3 J (0.2–0.6) x 100 Hz (50–80) ^b | 1200 | - | NR | 1800 | - | 588 | 18.6 | 0.061 | 0.7 | 1.43 | - |
| | K: 0.4 J (0.2–0.4) x 40 Hz (20–35) ^b | 998 | - | NR | (883–2760) ^b | (488–1020) ^b | (3.9–26.1) ^b | (0.38–0.105) ^b | (0.3–1.6) ^b | 0.3–1.6 | (0.63–3.33) ^b | - |
| Einkew 2021 [26] | 0.1–1 J x 7.5–200 Hz | 983 (360) ^a | 90 | 1.0 (0.4–2.0) ^b | 179 | - | 70 (30–162) ^b | (8.6–35.5) ^b | (0.028–0.116) ^b | (0.8–2.1) ^b | (0.48–1.25) ^b | - |
| | Low frequency: 0.5–6 J x 4–19 Hz | 900 | 85 ^a | 7.0 (4.7–16.6) ^b | (94–357) ^b | 10.15 (3.9–13.25) ^b | 319 | 3.4 | 0.296 | 6.8 | 0.15 | - |
| Koneily 2021 [27] | High frequency: 0.5–2 J x 20–49 Hz | 1100 | - | 5.4 (2.7–9.0) ^b | 1186 | 17 (5.8–27.5) ^b | 312 | 4.9 | 0.204 | 5.1 | 0.20 | - |
| | Higher frequency: 0.1–0.5 J x 50–200 Hz | 1170 | - | 7.2 (5.0–13.7) ^b | (905–2317) ^b | (2.8–7.4) ^b | (177–528) ^b | (2.8–7.4) ^b | (0.135–0.357) ^b | (3–8.7) ^b | (0.11–0.33) ^b | - |
| Taratkin 2021 [28] | URS: 0.15 J x 200 Hz/0.5 J x 30 Hz | 834 (298) ^a | 86 | 13.8 (11.8–25.0) ^a | 2743 (1451–4213) ^a | 22 (8.25–29) | 702 | 4.6 | 0.217 | 3.9 | 0.26 | - |
| | mPCNL: 0.8 J x 31–38 Hz | 882 (409) | 89 | 12.0 (7.0–20.1) ^a | 3285 (2210–3775) ^a | (600–930) ^b | 600 | 3.8 | 0.263 | 5.0 | 0.20 | - |
| Vaddi 2021 [29] | FW: 1–2 J x 6–30 Hz | 986 | 95 ^a | 13.1 (8.9) ^{a,d} | 1061 (807) ^{a,d} | 1108 (714) ^a | 14.4 (5.7) ^a | 14.4 (5.7) ^a | 0.069 (0.020) ^{a,d} | 0.94 (0.32) ^a | 1.06 (0.27) ^a | - |
| | DM: 0.1–0.2 J x 60–100 Hz | (303) ^{a,d} | - | - | - | 1275 (765) ^a | - | - | - | 0.77 (0.27) ^a | 1.30 (0.34) ^a | - |
| Barua 2022 [30] | URS: settings NS | - | 93 | 18.8 (11.5) ^a | - | 607.8 | - | - | - | 3.89 (3.52) ^a | 0.26 (0.12) ^a | - |
| | URS: settings NS | - | 86 | 25.0 (14.0) ^a | - | 407.0 ^a | - | - | - | 1.06 (1.09) | 0.92 (0.46) ^a | - |

Table 3 (continued)

| Study | Comparator (if any) and settings | Stone density (HU) | SFR (%) | Total energy (kJ) | Stone volume (mm ³) | Operative time (min) | Lasing time (s) | Laser energy consumption (J/mm ²) | Laser ablation efficiency (mm ³ /J) | Laser ablation speed (mm ³ /s) | Lasing time consumption (s/mm ³) | Laser efficacy (mm ³ /min) |
|--|---|------------------------------|-----------------------|-----------------------------|---------------------------------|---------------------------|-------------------------------|---|--|---|--|---------------------------------------|
| Corrales 2022 [31] | Olympus SOLTIVE: 0.3 J (0.2–0.6) x 100 Hz (50–180) ^b | 1200 (750–1300) ^b | – | – | 1800 (683–2760) ^b | – | 1380 (852–2322) ^b | 18.6 (9.5–26.1) ^b | 0.054 (0.038–0.105) ^{ba} | 1.16 (0.8–2.1) ^b | 0.86 (0.48–1.25) ^{ba} | – |
| | Quanta Fiber dust: 0.6 J (0.5–0.9) x 15 Hz (10–20) ^b | 950 (725–1125) ^b | – | – | 1125 (294–4000) ^b | – | 1583 (1020–3426) ^b | 14.3 (7.8–24.7) ^b | 0.070 (0.040–0.128) ^{ba} | 0.7 (0.4–1.2) ^b | 1.43 (0.83–2.50) ^{ba} | – |
| Sierra 2022 [32] | U: 0.6 J (0.5–1) x 10 Hz (10–20) ^b short pulse | 900 (400–1500) ^b | 100 ^d | – | 346 (147–1800) ^b | – | 1044 (792–1464) ^b | 8.7 (4.8–65.2) ^b | 0.115 (0.015–0.208) ^{ba} | 0.3 (0.2–1.3) ^b | 3.33 (0.77–5.00) ^{ba} | – |
| | K: 0.6 J (0.5–0.9) x 15 Hz (10–20) ^b short pulse | 950 (725–1125) ^b | – | – | 1125 (294–4000) ^b | – | 1583 (1020–3426) ^b | 14.3 (7.8–24.7) ^b | 0.070 (0.040–0.128) ^{ba} | 0.7 (0.4–1.2) ^b | 1.43 (0.83–2.50) ^{ba} | – |
| Taratkin 2022 [33] | Stone density | 657 (206) ^a | 89 ^a | 4.0 (2.1–7.17) ^b | 351 (132–754) ^b | – | 162 (90–408) ^b | 11.5 (6.8–16.8) ^b | 0.087 (0.060–0.147) ^{ba} | 2.1 (1.2–3.5) ^b | 0.48 (0.29–0.83) ^{ba} | – |
| | | 1306 (194) ^a | – | 3.9 (2.3–6.8) ^b | 264 (147–461) ^b | – | 174 (102–336) ^b | 16.2 (8.6–22.8) ^b | 0.062 (0.044–0.116) ^{ba} | 1.3 (0.9–2.5) ^b | 0.77 (0.40–1.11) ^{ba} | – |
| Vaddi 2022 [34] | Laser settings: 1–0.2 J x 100–150 Hz + 0.1–0.2 J x 200 Hz | 1018 (315) | 94 ^a | 12.6 (8.5) ^a | 1003 (684) ^a | 33.2 (16.1) ^{ad} | 1263 (693) ^a | 14.1 (5.0) ^a | 0.071 (0.019) ^{ba} | 0.76 (0.25) ^a | 1.32 (0.33) ^{ba} | – |
| | Laser settings: 1–2 J x 10–20 Hz + 0.1–0.2 J x 200 Hz | 956 (299) ^a | – | 13.7 (8.8) ^a | 1122 (798) ^a | – | 1121 (655) ^a | 14.6 (5.9) ^a | 0.068 (0.020) ^{ba} | 0.95 (0.28) ^a | 1.05 (0.24) ^{ba} | – |
| Shah 2020 [35] | 0.1–1 J x 100–300 Hz | 1300 (435) ^a | 48 h: 64.8; 1 mo: 100 | 18.4 (18.2) ^a | 2338 (1997) ^a | 39.9 (20.5) ^a | 605 (465) ^a | – | – | 5.02 (3.93) ^a | 0.20 (0.09) ^{ba} | – |
| TFL vs regular Ho:YAG/Ho:YAG MOSES technology | | | | | | | | | | | | |
| Chazi 2021 [36] | TFL: 0.4 J x 60 Hz | 846 (371) ^a | 68 | 11.7 (2.9–1.9) ^b | 1151 (2254) ^a | – | 534 (116–619) ^b | 21.2 (5.8–28.3) ^b | 0.047 (0.035–0.172) ^{ba} | 1.19 (0.4–1.4) ^b | 0.84 (0.71–2.50) ^{ba} | – |
| | Ho:YAG: 0.4 J x 60 Hz | 803 (303) ^a | 35 | 8.2 (3.3–1.0) ^b | 1089 (1613) ^a | – | 381 (340–699) ^b | 12.5 (5.8–16.6) ^b | 0.080 (0.060–0.172) ^{ba} | 4.1 (1.1–4.0) ^b | 0.24 (0.25–0.91) ^{ba} | – |
| Edison 2022 [37] | TFL: settings NS | – | – | – | 488 ^a | 55 ^a | – | – | – | – | – | 7.1 ^c |
| | Ho:YAG: settings NS | – | – | – | 373 ^a | 63 ^a | – | – | – | – | – | 4.35 ^c |
| Patil 2022 [38] | TFL: 0.1–1 J x 100–250 Hz | 1232 (263) ^a | 69 | 16.3 (15.0) ^a | 2294 (1503) ^a | 23.7 (11.3) ^a | 552 (422) ^a | 7.0 (4.0) ^a | 0.143 (0.052) ^{ba} | 5.2 (2.8) ^a | 0.19 (0.07) ^{ba} | – |
| | MOSES: 0.3–1.2 J x 20–80 Hz | 1212 (260) ^a | 78 | 21.9 (23.3) ^a | 2770 (1977) ^a | 41.9 (13.2) ^a | 679 (494) ^a | 9.0 (5.0) ^a | 0.111 (0.040) ^{ba} | 4.6 (2.1) ^a | 0.22 (0.07) ^{ba} | – |

SFR = stone free rate; PS = pulse shape; K = kidney; U = ureter; LT = lithotripsy time; NS = not specified; NR = not reported; TFL = thulium fiber laser; URS = ureteroscopy (covering both ureteral and kidney stones); mPCNL = mini-percutaneous nephrolithotomy; FM = fragmentation mode; DM = dusting mode; POD = postoperative day; mo = month.

^a Mean (standard deviation).

^b Median (interquartile range).

^c Not stated whether mean or median.

^d Overall for all comparator groups.

^e Calculated for this review.

3.5.1. *In vitro* studies

The two *in vitro* studies reflect highly standardized, idealized settings in attempts to assess laser ablation performance, which may impact the *in vivo* application of the laser technology. Therefore, data from *in vitro* studies cannot be extrapolated to the expected *in vivo* performance of a given laser, since environmental and surgical factors are likely to impact clinical findings. The two *in vitro* studies estimated ablated volume by measuring pulse craters on the stone surface, which is a limitation, as it omits qualitative assessment of the stone material broken off. Larger stone fragments broken off the “main stone” may falsely account for ablated stone volume [39]. Nevertheless, *in vitro* settings represent an adequate scenario for initial evaluation of any new technology or technique that may apply to lithotripsy.

Other *in vitro* studies on laser performance used weight as a metric for assessing ablation performance [39–43]; however, this approach entirely omits consideration of the volume. We believe that volume parameters are more clinically translatable. If the study setup requires weight as a primary outcome, volume parameters should be reported as well, if possible. A heavier weight may not mean a higher volume, as this depends on the stone density. Methods for determining the ablated volume should be evaluated in future studies, and may require additional tools and standardization. A recent study used known stone densities to

estimate the ablated volume [44], which is a feasible way for estimating this parameter in settings that only allow weight measurements.

3.5.2. Stone volume measurements

Among the *in vivo* studies included in this review, stone volume was estimated on the basis of preoperative CT scans, with the exception of one study that also used X-ray of the kidney, ureter, and bladder [32]. Estimation methods varied from the use of three-dimensional software-reconstructed volumes to ellipsoid formulas for calculations using measured dimensions. There are several ways to estimate volume [7,15,45], but there is no current standardized methodology. However, we would like to propose that in the era of low-dose noncontrast CT, CT should be the standard modality for radiological assessment of stone burden in studies on laser performance. The calculation method subsequently used for estimating volume is still a matter of debate.

3.5.3. Ablated stone volume

For *in vivo* studies, the preoperative stone volume and the postoperative-stone free rate play a key role in estimating the true ablated stone volume. Assessment of the stone-free rate was interchangeably based on CT, X-rays, or ultrasound in some studies. Of note, no study accounted for non-ablated remnant stone volume in ablation performance

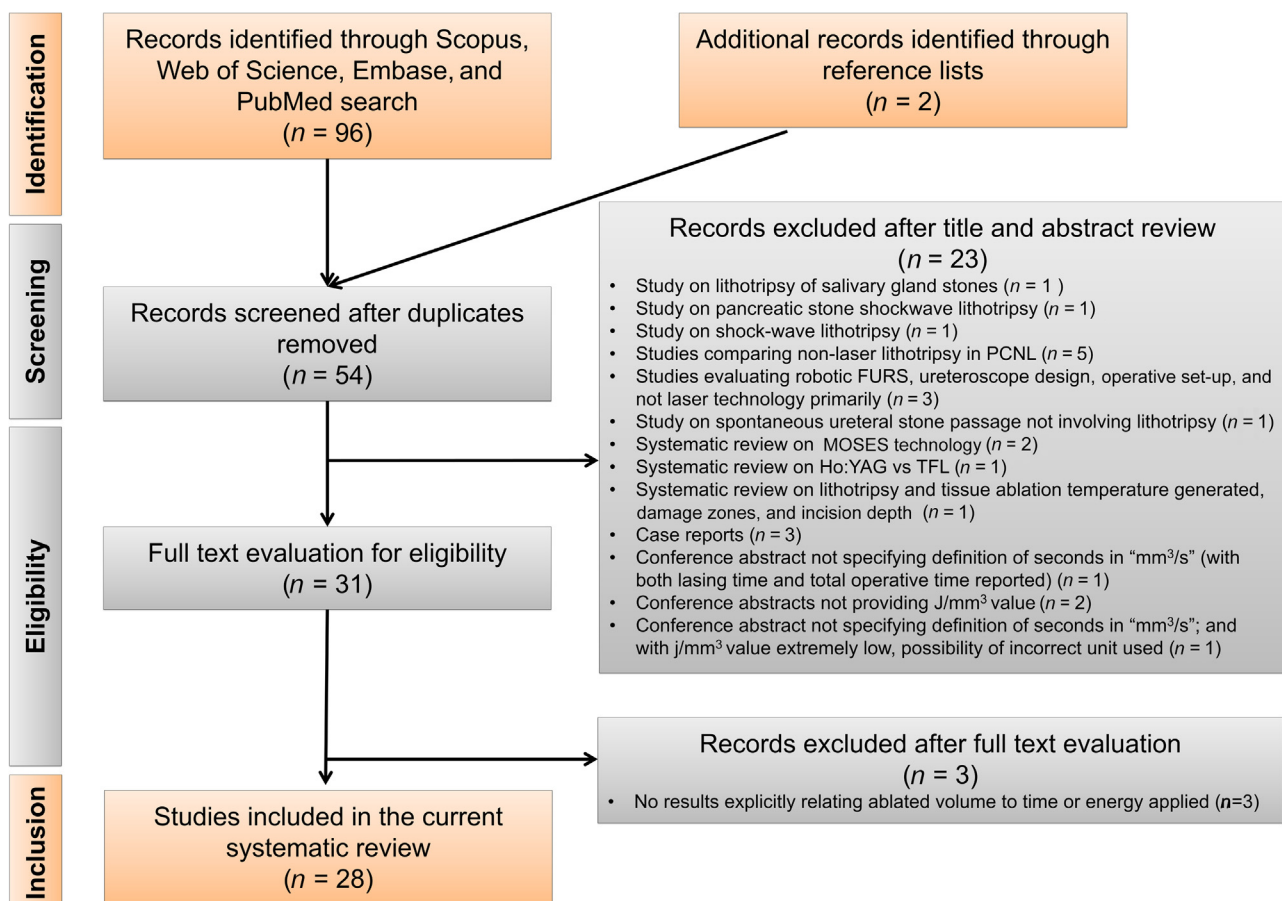


Fig. 1 – Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) flowchart. PCNL = percutaneous nephrolithotomy; FURS = flexible ureteroscopy; TFL = thulium fiber laser.

measurements, a parameter that is technically challenging to measure. Consequently, the laser energy consumption and efficiency values reported may have arguably been affected by the postoperative stone-free rate. In fact, stone-free rates in the studies included in the review varied widely from as low as 35% up to a 100%. The study with high risk of bias had starkly different stone-free rates in the comparator groups (35% vs 68%) [36]. In addition, when basketing and evacuation of fragments are included in the study methodology [16,18,22,27,35,37,38], this would arguably increase the outcome values for laser ablation efficiency and laser ablation speed, especially in PCNL studies [22,27,35,38]. The values reported arguably reflect concomitant non-laser-related procedural contributors to stone removal. Thus, the measurement methodology, the stone-free rate, and the inclusion of stone evacuation may contribute to the wide range of values for laser ablation efficiency and laser ablation speed in studies on laser performance.

3.5.4. Terminology

In referring to outcomes that relate stone volume to energy or time, eight studies used the term “efficiency” [13–16,22,28,35,36] and ten used “efficacy” [16,23,24,26,27,29,32–34,36] (Table 4). For energy outcome metrics, only one *in vitro* study reported values in mm^3/J

(laser ablation efficiency) [13], while 20 studies reported values in J/mm^3 (laser energy consumption) [8,12,15–19,21,24–29,31–34,36,38]. The terminology used to describe results for mm^3/J and J/mm^3 also differed widely between different studies. Of note, three studies [24,27,36] termed laser energy consumption (J/mm^3) as “ablation efficacy” or “ablation efficiency”, then astonishingly and mistakenly interpreted their data as “the higher, the better”, when in fact the exact opposite is the case. It is conceivable that due to the terminology used in these studies, the authors unknowingly interpreted laser energy consumption (J/mm^3) falsely, when it is in fact inversely proportional to laser ablation efficiency (mm^3/J). Naturally, this can also be confusing to readers.

There was also variability in describing time-related outcomes. Most studies included lasing time, with other time periods reported including “total operative time” and “operative time”, and two studies using “lithotripsy time” (first laser activation to the end of the last laser activation) [8,18]. Of the two studies reporting laser efficacy (mm^3/min), one defined “operative time” from the beginning of the laser procedure until removal of the last stone fragment [14], while the other used “total operative time” without further elaborating how this was defined [37]. All the studies that reported laser ablation speed (mm^3/s) specifically described that the time unit referred to lasing time, which is directly

Table 4 – Terms used for volume-related units in the studies on laser performance

| Study | J/mm^3 | mm^3/J | mm^3/s | s/mm^3 | mm^3/min |
|----------------------|---|------------------------|--|------------------------|------------------------------|
| Panthier 2020 [12] | Required energy to treat 1 mm^3 | – | – | – | – |
| King 2022 [13] | – | Ablation efficiency | – | – | – |
| Alghamdi 2020 [14] | – | – | – | – | Laser efficiency |
| Panthier 2021 [15] | Efficiency ratio, volumetric energy | – | Ablation rate | – | – |
| Ventimiglia 2021 [8] | Energy required to ablate 1 mm^3 of stone volume | – | Ablation speed | – | – |
| Panthier 2022 [16] | Efficiency ratio, volumetric energy | – | Efficacy ratio, ablation rate | – | – |
| Shrestha 2022 [17] | Laser energy used to ablate 1 mm^3 of stone | – | Ablation speed | – | – |
| Majdalany 2021 [18] | Energy used per unit stone volume | – | Fragmentation speed | – | – |
| Antoine 2022 [19] | Energy use rate | – | Stone ablation rate | – | – |
| Mullerad 2017 [20] | – | – | – | – | Fragmentation rate |
| Mekayten 2019 [21] | Energy | – | – | Laser time per volume | – |
| Dunne 2021 [22] | – | – | Efficiency score | – | – |
| Wang 2021 [23] | – | – | – | – | Stone fragmentation efficacy |
| Enikeev 2020 [24] | Energy for ablation of 1 mm^3 , ablation efficacy | – | Ablation speed | – | – |
| Corrales 2021 [25] | Amount of energy needed to ablate 1 mm^3 of stone volume | – | Ablation speed | – | – |
| Enikeev 2021 [26] | Energy for ablation of 1 mm^3 , ablation efficacy | – | – | – | Ablation speed |
| Korolev 2021 [27] | Energy for ablation of 1 mm^3 , ablation efficacy | – | Ablation speed | – | – |
| Taratkin 2021 [28] | Energy for ablation of 1 mm^3 , ablation efficacy | – | Stone ablation speed | – | – |
| Vaddi 2021 [29] | Laser efficacy | – | Ablation speed | – | – |
| Batra 2022 [30] | – | – | Stone fragmentation rate | – | – |
| Corrales 2022 [31] | Not defined; referred to directly as J/mm^3 | – | Ablation speed | – | – |
| Sierra 2022 [32] | Laser efficacy | – | Ablation speed, ablation rate | – | – |
| Taratkin 2022 [33] | Ablation efficacy | – | Ablation speed | – | – |
| Vaddi 2022 [34] | Laser efficacy, energy required for ablation of 1 mm^3 of stone volume | – | Ablation speed | – | – |
| Shah 2020 [35] | – | – | Stone fragmentation rate, stone fragmentation efficiency | – | – |
| Ghazi 2021 [36] | Ablation efficacy, ablation efficiency | – | Ablation speed | – | – |
| Edison 2022 [37] | – | – | – | – | Operating speed |
| Patil 2022 [38] | Energy per volume of stone, energy consumed per volume of stone | – | Stone fragmentation rate | – | – |

Table 5 – Proposal of a standardized terminology for outcomes in laser lithotripsy studies

| Term | Unit | Interpretation | Numerator | Denominator | Scientific relevance | Clinical relevance |
|--|----------------------|------------------------|--|--|---|---|
| Laser ablation efficiency | mm ³ /J | The higher, the better | Ablated stone volume | Total laser energy | <i>In vitro</i> outcome comparisons | Highly efficient lasers can operate very efficiently with low-power settings, which is of relevance considering the risk of thermal damage associated with high-power settings. |
| Laser ablation speed | mm ³ /s | The higher, the better | Ablated stone volume | Lasing time | Correlates directly with average power rather than laser ablation efficiency. The mean stone volume, total energy, and mean lasing time are therefore the minimal set of variables that must be detailed to correctly interpret this outcome. | Little clinical relevance since it is recommended that the maximum power is limited to prevent thermal damage due to heat generated during laser lithotripsy. |
| Laser efficacy | mm ³ /min | The higher, the better | Clearance of stone volume (<i>in vivo</i>) | Total operative time, from insertion of first instrument to removal of last instrument | Accounts for the whole procedure time, including lithotripsy, stone basketing, stone dust suction, and any other relevant steps. | Best outcome for comparing the overall performance of a laser together with the specific technique used (including laser settings). |
| Consumption | | | | | | |
| Laser energy consumption | J/mm ³ | The lower, the better | Total laser energy | Ablated stone volume | <i>In vivo</i> outcome comparisons | Estimation of total laser energy needed to ablate a given stone volume. Such calculations could help with preoperative planning. |
| Lasing time consumption | s/mm ³ | The lower, the better | Lasing time | Ablated stone volume | Correlates directly with average power rather than laser energy efficiency. | May help with preoperative planning, although this parameter is mainly dictated by average power, which should generally be kept within a limited and safe margin. |
| Total operative time laser consumption | min/mm ³ | The lower, the better | Total operative time | Ablated stone volume | Accounts for the whole procedure (considering total operative time, or total experimental time), and therefore time required for subsequent steps such as stone basketing and dust suction, among others | Best outcome for estimating operative time for a given stone volume. May help with preoperative planning, although this outcome is mainly dictated by average power, which should be kept within a safe margin. |

correlated with average power. Three studies in the screening process had ambiguity regarding whether the time component referred to total operative time or lasing time [16,46,47].

3.5.5. Proposal for a standardized terminology for reporting on laser performance

Considering the above, there is a need for a standardized terminology for describing laser performance. To this end, we propose a standardized terminology for outcomes in studies on laser lithotripsy (Table 5).

According to the *Cambridge English Dictionary*, efficiency is “the quality of achieving the largest amount of useful work using as little energy, fuel, effort, etc. as possible” [48]. We thus propose the use of “efficiency” in describing the volumetric ablation performance in relation to the energy resource used – “laser ablation efficiency” (mm^3/J): the higher the value, the more efficient is the laser. To differentiate units with inverse relationships, we propose use of “consumption” to describe the resources (energy or time) needed per unit volume (J/mm^3 , s/mm^3 , min/mm^3), as detailed in Table 5. Thus, the lower the value for these measures, the better. When referring to laser performance in terms of lasing time spent on ablation, we propose the term “laser ablation speed” (mm^3/s) to reflect the volume ablated per unit of lasing time.

Efficacy is defined as “the ability, especially of a medicine or a method of achieving something, to produce the intended result” [49]. To describe the overall efficacy of the procedure using a particular laser, we propose the term “laser efficacy” (mm^3/min) for clearance of stone volume per unit of total operative time. In a lithotripsy procedure, this accounts for non-lasing time, including stone basketing [50], percutaneous sheath evacuation [51], and stone dust suction [52]. These ancillary maneuvers are closely related to the ability of the laser to produce small fragments or fine dust. For example, a laser would be highly efficacious in the context of mini-PCNL if it can achieve adequately sized fragments in a short time, facilitating faster fragment evacuation. Another example would be laser efficacy in ureteroscopy using a dusting technique. A higher efficacy would be when dusting time is short, yet with the laser being able to produce fine dust and consequently a short suction and evacuation time for the dust. Of note, a high laser ablation speed may not translate to greater laser efficacy. An example would be a laser capable of ablating a large volume of stone per unit time, but producing numerous large fragments that would need a long total operative time to clear out. To account for the whole procedure, total operative time should be defined from insertion of the first instrument to removal of last instrument. Importantly, laser efficacy must be reported within the context of a particular procedure and specific technique.

Finally, we propose that future studies on laser performance should always present results in terms of ablated stone volume, total laser energy, lasing time, and total operative time (where applicable), in addition to values calculated for laser ablation efficiency (mm^3/J), laser energy consumption (J/mm^3), and laser ablation speed (mm^3/s). When possible, studies should strive to report volume outcomes owing to their clinical applicability to radiological stone volume measurements.

3.5.6. Limitations

There are limitations to our review that need acknowledgment. First, we limited our review to studies evaluating laser performance on the basis of ablated stone volume and did not include studies on ablated stone weight. Nevertheless, and as stated above, volume-related parameters are more clinically relevant, as stones are measured radiologically by dimension and volume, and not by weight. Second, our methodology is based on a search of current laser performance metrics using volume, energy, and time units, and a subsequent review of the corresponding terminology used. We chose this approach rather than a primary search for the terms currently used (eg, efficiency, efficacy, speed), as the metrics corresponding to these terms may not reflect laser performance in the specific volumetric units of interest (eg, weight), which is not the aim of the review. Third, information for some data fields was limited in some conference abstracts. Nonetheless, for completeness, we opted to include these conference abstracts. Finally, heterogeneity for the laser settings, study setup and study protocols meant that no direct conclusions could be drawn from comparison of results between studies. Therefore, no meta-analysis was performed.

3.5.7. Future research

There is a strong need for consensus on standardized terminology for laser performance in the era of volumetric measurement of stone burden. This will provide clarity in interpretation of performance results, forming a solid foundation for future research in assessment of laser performance.

4. Conclusions

In conclusion, a wide range of laser performance metrics relating stone volume to energy or time are used in the literature, with corresponding differing terminology. Urologists need to interpret laser performance studies with care, to consider the terms used, and the methodology of measuring the ablated volume and stone-free rates before applying results to their clinical practice. The standardized terminology proposed in this study may help in the interpretation and comparison of future studies on laser lithotripsy.

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Study concept and design: Traxer, Keller.

Acquisition of data: Kwok, Keller.

Analysis and interpretation of data: Kwok, Keller.

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Appendix A. Supplementary data

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