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Miniaturizing the approach to upper tract renal calculi: Is smaller always better? A narrative review

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Abstract

Newer modalities for treating upper tract urinary stones focus on maintaining and improving outcomes, reducing complications, and optimizing patient care. This narrative review aims to outline novel miniaturized endourological innovations for managing upper tract calculi.

Keywords: Novel innovation; Endourology; Calculi; Percutaneous nephrolithotomy; Narrative review

1. Introduction

Renal stone disease is one of the most common urological conditions, and its incidence is increasing. In the United States, rates have been reported as high as 1 in every 11 adults, whereas worldwide, the prevalence of nephrolithiasis is approximately 8 cases per 1000 adults.[1]

Both the European Association of Urology and American Urological Association guidelines recommend percutaneous nephrolithotomy (PCNL) as the first treatment option for large renal calculi (>20 mm) and staghorn calculi, with a stone-free rate (SFR) of 95%. Other options for large renal stones include retrograde intrarenal surgery (RIRS) and extracorporeal shockwave lithotripsy.[2–4] Percutaneous nephrolithotomy may also be an alternative to RIRS for the treatment of renal calculi measuring between 10 and 20 mm because of better SFRs achieved by a single procedure.[2]

Percutaneous access to renal collection was first described in 1955 by Dr Willard Goodwin as a minimally invasive alternative to traditional surgery for hydronephrosis. In 1976, the first stone retrieval through a percutaneous nephrostomy tract was successfully performed.[5,6]

The accepted conventional PCNL technique uses an access sheath between 24 and 30 Fr. Complications include blood loss and the need for blood transfusions, iatrogenic injury to adjacent organs, urinary tract infections, urosepsis, and renal parenchymal loss due to large tract insertions. With the rapid progress in medicine and surgical innovation, the procedure has advanced greatly with more sophisticated equipment and ever-smaller PCNL tract sizes in a bid to become more minimally invasive while maintaining high SFRs and low complication rates.[7]

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This narrative review aimed to explore an array of minimally invasive PCNL (MIPNL) techniques and objectively analyze them using the currently available literature. Publications from the start of 2012 (within the last decade) were identified by searching the MEDLINE, Embase, Cochrane Library, and DOAJ databases, and bibliographies. The inclusion criterion was the use of a miniaturized version of the standard PCNL or a miniaturized version in conjunction with an alternative technique. The exclusion criteria were non-English publications and pharmacological interventions.

2. Novel innovation in approaching upper tract calculi

2.1. Mini–percutaneous nephrolithotomy

The mini-PCNL or "mini-perc" was the first described miniaturized version of the standard PCNL technique. Jackman et al.[8] (1998) reported a series of adult mini-PCNL procedures using a 13-Fr access sheath. This technique uses an access sheath that varies in size from 11 to 20 Fr. A rigid pediatric cystoscope (7 Fr) or a flexible ureterorenoscope (9.5 Fr) was used within an 11-Fr access sheath with either a laser fiber or a lithotrite for stone destruction. The fragments were irrigated, suctioned, or sequentially removed using a grasping device. Jackman reported that this technique provided relatively good stone clearance while reducing blood loss and length of hospital stay. Recently, Bozzini et al.[9] described a significant decrease in the complication rate (4.2% vs. 13.6%) while maintaining comparable results with regard to the need for retreatment, hospitalization length, operating time, and SFR (82.9% vs. 86.3%) at 3 months when comparing mini-PCNL to conventional (maxi) PCNL.

A retrospective report by Hu et al.[10–12] reported a notable reduction in the need for blood transfusion compared with conventional PCNL; however, surprisingly, complication rates were 20.1%, with the majority of these (81%) being Clavien-Dindo grade 1 or 2.

Proietti et al.[13] reported that the hematocrit drop and duration of hospitalization were lesser for mini-PCNL than for conventional PCNL; however, they reported a longer operation time in the mini-PCNL group. The SFR was 94% for the conventional PCNL group and 77.8% in the mini-PCNL group for the treatment of calculi <20 mm in diameter.

This demonstrates that smaller tracts may not always provide better results, particularly with stone clearance, and there is differing data regarding complication rates among mini-PCNL procedures.

2.2. Chinese minimally invasive percutaneous nephrolithotomy

Since the early 1990s, Chinese urologists have been using a smaller tract than conventional techniques to perform PCNL, which they call MIPNL. This technique involves fluoroscopy-guided puncturing of the desired calyx using an 18-gauge needle. Tract dilation was then serially performed using metal dilators from 8 to 15 Fr and a matched 16-Fr sheath was placed. From this sheath, an 8/9.8-Fr rigid ureteroscope was placed, and a holmium:YAG laser or pneumatic lithotripter was used to fragment the calculi.[14]

In a single-center study performed by Salih et al.[15] in 2019, the safety and efficacy of MIPNL in the treatment of renal calculi ≤20 mm was evaluated. In this cohort of 67 patients who underwent MIPNL, 55 (82.0%) patients were stone free after MIPNL, the operative time ranged from 40 to 190 minutes (mean, 74.58 ± 30.34 minutes), and the hospital stays ranged from 2 to 7 days (mean, 3.34 ± 1.62 days). Intraoperative complications were reported in 4 (5.0%) patients. Bleeding requiring blood transfusion occurred in 1 patient (1.5%), and perforation of the renal collecting system occurred in 3 patients (4.5%). The reported postoperative complications were urine leakage in 5 (7.5%) patients and postoperative fever in 6 (9.0%) patients.

Similar results were reported in a single-center study by Huang et al.[14] In this study, a cohort of patients had a solitary kidney. In a small cohort of 41 patients, they found the mean operative time to be 71.3 ± 23.5 minutes (range, 40–139 minutes). The SFR was 85.4%, and there were no intraoperative complications. Postoperative complications occurred in 5 (12.2%) patients with postoperative fever (temperature of 38.5°C or greater). These results are consistent with those of Salih et al. and substantiate the benefit of this miniaturized PCNL technique by lowering operative times, using smaller renal access tracts, and decreasing patient stay in the hospital while maintaining high SFRs and low complication rates.

2.3. Supermini–percutaneous nephrolithotomy

Zeng et al.[16] first described the 2 generations of supermini-PCNL (SMP) in 2016. The first generation was replaced because of its limited ability to provide adequate irrigation. Thus, a second generation was developed to address this issue. This novel technique uses a 7-Fr nephroscope with enhanced irrigation and a modified 10 to 14-Fr access sheath with a suction-evacuation function. A comparison between the SMP and conventional PCNL was performed by Guddeti et al.[17] in 2020. A total of 150 patients presenting with renal calculi <2 cm in size were randomized to either conventional PCNL (Group 1) or SMP (Group 2). This study found that SMP is as effective as conventional PCNL for managing renal calculi <2 cm in size, with improved safety. Although SMP is associated with a longer operative time, it has a significantly lower incidence of bleeding (mean drop in hemoglobin 3.0 [4.9] vs. 7.5 [6.5] g/L, $p < 0.001$) and postoperative pain (pain score at 24 hour was significantly lower in Group 2 at 0.3 [0.46] vs. 0.75 [0.53], $p < 0.001$) and a shorter hospital stay (Group 2 at 28.38 [3.6] vs. 39.84 [3.7] hour, $p < 0.001$).

In 2018, Zeng et al.[18] described a prospective study of the SMP and RIRS. A total of 160 patients were randomized into 2 groups. Although stone parameters were comparable between the 2 groups (15 vs. 14.3 mm), the 1-day and 3-month SFR were significantly higher in the SMP group (day 1: SFR 91.2% vs. 71.2%, p = 0.001; 3 months: 93.8% vs. 82.5%, p = 0.028). There were no significant differences in the operative time, hospital stay, or complication rates between the groups.

In a study by Xu et al.[19] in 2018, SMP was compared with flexible ureteroscopy (F-URS) in a cohort of obese patients with body mass index >30 kg/m^2. Supermini-PCNL was noted to have a significantly shorter operation time, higher 3-day postoperative SFRs, lower overall costs, and fewer Stage 2 procedures. However, by contrast in this cohort, patients who underwent F-URS had significantly lower postoperative complications as well as shorter hospital stays.

2.4. Ultramini–percutaneous nephrolithotomy

Ultramini-PCNL (UMP) is a relatively new addition to the vast array of MIPNL techniques. Desai et al. described the procedure using a 3-Fr telescope with a specially designed 7.5-Fr nephroscope that allowed the surgeon to perform PCNL within an 11- to 13-Fr sheath.[12] In a retrospective study, the authors analyzed the outcomes of 36 patients with renal calculi measuring <20 mm. The average operative time was 59.8 ± 15.9 minutes (30–90 minutes); the SFRs at postoperative day 1 and month 1 were 88.9% and 97.2%, respectively. The mean hospital stay was 3.0 ± 0.9 days (2–5 days), and complications were noted in 6 patients (16.7%).[20]

In 2017, Haghighi et al.[21] compared the results of UMP with those of conventional PCNL. In their study, they used a slightly different UMP setup consisting of a 9.8-Fr ureteroscope through a 16-Fr sheath. This does not fall within typically described versions of the UMP. Seventy patients underwent either UMP (Group A) or conventional PCNL (Group B); they found that there were statistically significant differences in postoperative hemoglobin values (13.14 g/dL [A] vs. 11.52 g/dL [B]), hemoglobin drop (1.65 g/dL [A] vs. 3.13 g/dL [B]), transfusion rate (5.71% [A] vs. 11.4% [B]), duration of hospitalization (2.32 days [A] vs. 3.60 days [B]), and postoperative visual analog scale pain score (4.3 [A] vs. 5.7 [B]) between the groups. There were no significant differences in operative time (48 minutes [A] vs. 51 minutes [B]), need for auxiliary procedures, or SFRs (93.58% [A] vs. 94.60% [B]).

Another study performed in India in 2016 by Agrawal et al.[22] examined the outcomes of 120 patients who underwent UMP between 2012 and 2014. All patients underwent UMP using a 3-Fr nephroscope, a 7.5-Fr inner sheath, and an 11- or 13-Fr outer metallic cannula. They found that the mean operative time was 39.7 ± 15.4 minutes, and the mean postoperative hospital stay was 22.3 ± 2.2 hours. Postoperatively, 6 (5%) patients had residual fragments measuring ≤4 mm. At the 2-week follow-up, the stone-free status was >99% (119/120 patients). There were no significant postoperative complications. The results of UMP are consistent throughout the literature, confirming that UMP is an effective and safe procedure for managing renal calculi, and often has better outcomes than conventional PCNL.

2.5. Micro–percutaneous nephrolithotomy

Micro-PCNL is a novel technological advancement in the field of percutaneous management of renal calculi and has a promising future for the treatment of nonbulky urolithiasis. Indicated for the management of calculi <15 mm, this technique first reported in 2011 by Desai et al.[23] makes use of a 4.85-Fr (16-gauge) "all-seeing needle" in which renal access and laser stone fragmentation are performed in a single-step procedure. Calculi were dusted using this technique, and stone fragments were not actively removed and were expected to pass spontaneously.

A cohort of 10 patients underwent micro-PCNL and found a mean 1.4 ± 1.0 g/dL hemoglobin decrease and a mean hospital stay of 2.3 ± 1.2 days. The SFR at 1 month was 88.9%. In 1 patient, intraoperative bleeding and obscured vision were found, and conversion to mini-PCNL was required. No postoperative complications occurred, and auxiliary procedures were not required.[23]

In 2019, Jiang et al.[24] compared micro-PCNL and F-URS for the management of lower calyceal calculi measuring <2 cm. For treating lower calyceal calculi of ≤2 cm, the "all-seeing needle" micro-PCNL group had shorter operative time than F-URS, whereas no significant differences between the 2 groups with respect to mean hemoglobin reduction, complications, length of stay, and SFR were found.

When compared with mini-PCNL, a meta-analysis performed by Gao et al.[25] found that micro-PCNL could produce an SFR comparable with that of mini-PCNL. Micro-PCNL was associated with a lower hemoglobin drop, whereas mini-PCNL was associated with a lower renal colic rate. In addition, the operative and hospital stay durations for the 2 procedures were similar. Notably, the Double J stent insertion rate was higher in the micro-PCNL group likely owing to the fact mentioned previously that stone fragments are expected to pass spontaneously and thus D-J stents may aid in this process.

2.6. *Clearpetra™*

Another novel innovative sheath design, Clearpetra™, is a modification of the miniaturized PCNL technique. Similar to the SMP, which consists of a 16-Fr sheath externally plugged and equipped with a lateral oblique arm connected to an aspiration system, it allows continuous irrigation and lapaxy by aspirating the stone fragments together with the irrigation fluid during lithotripsy.[26] As stated previously, one of the largest pitfalls of miniaturized systems is the inability to remove stone fragments and poor visibility, which is ameliorated by the use of a vacuum-assisted mini-PCNL (vmPCNL) with its continuous semi–closed circuit of irrigation and suction.

In a cohort of 175 patients randomized to either the vmPCNL or MIPNL, Lievore et al.[26] found that the operating theatre (OT) was shorter in the vmPCNL group than in the MIPNL group (90 vs. 120 minutes, $p = 0.001$). The SFR was higher in the vmPCNL group than in the MIPNL group (89.4% vs. 78.8%, $p = 0.04$). Postoperative decrease in hemoglobin level and length of hospital stay were similar between the groups.

Recently, Zanetti et al.[27] reported outcomes in a cohort of 122 patients who underwent vmPCNL. They found stone clearance in 71.3% of patients, with a median OT of 90 minutes, and observed lower postoperative fever (7.4%) and transfusion (0.8%) rates than those reported in the literature for conventional PCNL (10.8% and 7%, respectively).

It was concluded that the principles of mini-invasiveness were respected and that short OTs and controlled intrarenal pressures may play a role in the prevention of infectious complications compared with conventional PCNL.

2.7. *Needle perc*

The most recent innovation in the field of PCNL is the needle perc. Su et al.[28] described an instrument used to overcome some of the drawbacks of RIRS, particularly those of lower pole stones in kidneys with a steep infundibulopelvic angle or in a diverticulum. It uses a 4.2-Fr needle to achieve renal access under ultrasound guidance, and stone fragmentation or dusting is completed through a 200-μm laser fiber within 1 of the 3 available ports. The instrument also has a port for a 0.6-mm optical fiber and another for the irrigation fluid. The term "needle perc–assisted endoscopic surgery" (NAES) has been described when needle perc combined with standard PCNL or RIRS is used to treat complex renal stones, lower pole stones, or caliceal diverticular stones. In this study, 119 patients were treated with NAES. The mean operative time was 79.8 ± 28.9 minutes (excluding positioning of patient), and the SFR at 1 month was 88.2%. The overall complication rate in the patients who underwent NAES was 11.8%. Another study conducted by Xiao et al.[29] examined needle performance and its efficacy in a pediatric population. Although the study included only 8 patients, the SFR at 1 month postoperatively was 100%. This, coupled with the reduced operative time (mean operating time, 49.2 minutes), highlights the effectiveness of this novel technique.

Another study conducted in China by Xiao et al.[30] analyzed the outcomes of 24 patients who underwent needle perc. The patients were all required to have a single renal stone of 15 mm or less. Of the 24 patients in the study, only 3 (12.5%) had minor complications (Clavien-Dindo II or less), and no blood transfusions were required postoperatively in the study population. The needle perc technique is evidence of the ever-advancing and miniaturizing process of PCNL and highlights the ability to maintain high SFRs while mitigating complications.

3. Discussion

Globally, the incidence of nephrolithiasis is increasing owing to socioeconomic and climatic factors.[31] There is an ever-increasing need to manage these patients with the goal of increasing SFRs while simultaneously lowering important factors, such as hospital stay time, operative time, blood loss, and the need for follow-up procedures. Percutaneous nephrolithotomy is widely considered the criterion standard for the treatment of large or complex renal calculi. First described in 1976 by Fernstrom and Johansson,[6] the procedure has been constantly evolving to improve SFRs while lowering complications related to tract size. Standard PCNL traditionally uses tract sizes ranging from 24 to 30 Fr and typically results in an SFR of up to 100%. When considering complications, such as blood loss and the need for blood transfusion, standard PCNL typically has higher rates owing to the larger tract size and is compounded in complex stone burdens, as more than one tract is often needed to obtain stone clearance. ElSheemy et al.[32] compared the management of all stone types, including staghorn, multiple calyceal, and simple calculi, by mini-PCNL with that by standard PCNL. Mini-PCNL has been proven to result in shorter hospital stays, higher rates of tubeless procedures, and significantly lower complication rates, including those associated with blood transfusion. Importantly, the study found that SFRs were comparable in single calculus or low stone burdens of ≤2 cm, but when the stone burden was multiple or large (>2 cm), mini-PCNL had significantly lower SFR (89.9% vs. 96%, $p = 0.022$).

The stone-free postintervention rate is a key indicator of the effectiveness of a specific PCNL technique. There is currently no consensus on the definition of stone-free status. In 2013, Somani et al.[33] proposed a simple classification system using levels based on the fragment size and the modality used at follow-up, providing a detailed description of SFR grades. Generally, stone-free status is defined as no residual calculi or the presence of residual calculi ≤4 mm in size at 1 month after the procedure.[34] As in the study by Gao et al.,[25] this can be analyzed using different imaging techniques ranging from simple radiography to computed tomography imaging with the criterion standard method for residual fragment detection as a postoperative noncontrast spiral computed tomography; however, a second-look procedure may also be used.[34] The interval postintervention of when the stone burden is reassessed is also important, as fragments may not be actively removed or may be allowed to pass gradually, thus negatively affecting the SFR if measured directly after the procedure. All miniaturized PCNL techniques offer relatively high SFRs, as described in a

Table 1

Tabulation of sheath diameter (Fr) sizes and ranges available within all miniaturized options for the treatment and access of upper tract calculi.

Nomenclature	Access sheath size (Fr)	Reference
Standard PCNL	24–30	Thapa et al.[35]
Mini-PCNL	11–20	Jackman et al.[8]
Chinese minimally invasive PCNL	14–20	Li et al.[40]
Super-mini-PCNL	10–14	Zeng et al.[16]
Ultra mini-PCNL	11–13	Desai et al.[20]
Micro-PCNL	4.85	Desai et al.[23]
Needle perc	4.2	Su et al.[28]
Clearpetra™	16	Lievore et al.[26]

PCNL = percutaneous nephrolithotomy.

meta-analysis by Thapa and Niranjan,[35] which are comparable with those of standard PCNL. Similarly, Kallidonis et al.[36] analyzed multiple randomized control trials undertaken by different research groups comparing miniaturised-PCNL (mPCNL) techniques to conventional techniques with regard to SFR; the majority did not find any significant differences between the groups. Consistent with other studies, mPCNL techniques were noted to result in a lower drop in hemoglobin levels, which led to a decreased rate of blood transfusion. In addition, mPCNL was associated with decreased duration of nephrostomy and shorter hospital stay.

The benefits of using smaller working tracts come with their own set of drawbacks; however, these are mostly related to operative time and increased intrarenal pressure. In the literature, mPCNL techniques have been consistently described as time consuming. This was mostly related to the inability to evacuate larger stone fragments through the smaller tract. Laser lithotripsy is an effective way of performing stone fragmentation; however, it takes longer than other modalities, such as pneumatic lithotripsy, which can sometimes be performed through a smaller tract.[37,38]

Irrigation within these smaller tracts may also be less effective in preserving good stone visualization during the procedure, thus prolonging the operative time. Another disadvantage of mPCNL is the increased intrarenal pressure associated with smaller sheaths. Using a porcine model, Loftus et al.[39] demonstrated how sheath and endoscope sizes affect intrarenal pelvic pressure and the risk of postoperative infectious complications.

In this study, uropathogenic *Escherichia coli* was grown, and 109 cells were instilled into the porcine renal pelvis through retrograde access for 1 hour. Percutaneous access used a 14/16-Fr, 20-cm ureteral access sheath for the mini arm and a 30-Fr sheath for the standard arm. Nephroscopy was simulated using either an 8/9.8-Fr semirigid ureteroscope or a 26-Fr nephroscope for 1 hour while intrarenal pelvic pressure was continuously monitored. Blood and tissue cultures of kidney, liver, and spleen biopsies were collected postoperatively. The results showed that intrapelvic pressures were higher in the mini group, 18.76 ± 5.82 versus 13.56 ± 5.82 mm Hg ($p < 0.0001$). Time spent above 30 mm Hg was greater in the mini arm, 117.0 versus 66.1 s ($p = 0.0452$). All pigs had positive kidney tissue cultures, whereas spleen cultures were positive in 100% and 60% of the pigs in the mini and standard arms, respectively ($p = 0.0253$). Ninety percent and 30% had positive liver tissue cultures in the mini and standard arms, respectively ($p = 0.0062$). Blood cultures were positive in 30% of the pigs in the mini arm compared with none in the standard arm ($p = 0.0603$). This demonstrated a higher rate of end-organ seeding secondary to increased intrarenal pressure during mPCNL; although demonstrated in a porcine model, conclusions can be made about the higher risk of postoperative infections in humans.

4. Conclusions

Minimally invasive PCNL techniques have been extensively described in the literature, with various modifications (Table 1 and Fig. 1), and

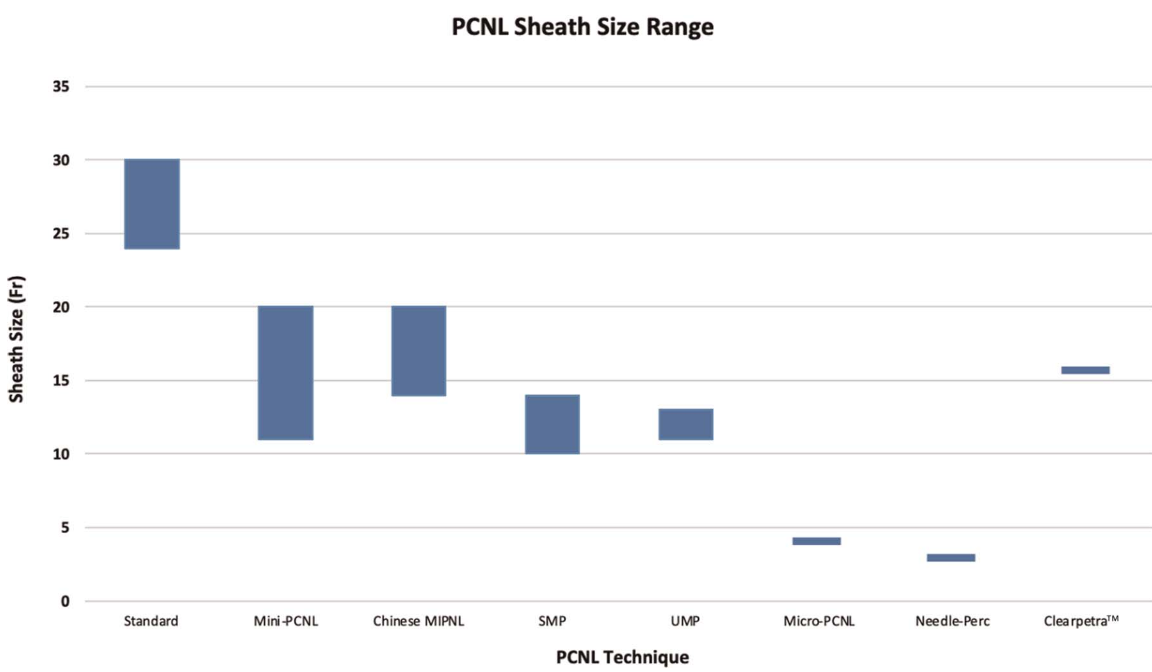

Figure 1. Diagrammatic representation of the sheath diameter (Fr) sizes and ranges available within all the miniaturized options available for upper tract calculi. MIPNL = minimally invasive percutaneous nephrolithotomy; PCNL = percutaneous nephrolithotomy; SMP = supermini-PCNL; UMP = ultramini-PCNL.

have shown improved efficacy in treating small-to-medium renal calculi. These techniques offer a reasonable alternative to standard PCNL, with a similar SFR and the added benefits of a shorter hospital stay, fewer postoperative complications, and higher tubeless rates. Although not globally accepted as the gold standard for managing renal calculi, mPCNL techniques are gaining traction among urologists and, with increasing literature on the subject, may become the preferred PCNL technique in the future. More studies with larger cohorts are required to better understand the effectiveness, safety, and limitations of these novel procedures.

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Statement of ethics

Not applicable.

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DDSF, AA: Conceptualization, data curation, formal analysis, investigation, methodology, validation, visualization, writing—original draft; ASB: Data curation, formal analysis, investigation, methodology, supervision, writing—review and editing.

Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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