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Original Article

Comparison of the cleaning effectiveness of pulsed vacuum cleaning and disinfection machine versus spraying cleaning and disinfection machine for rigid endoscope instruments

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Abstract

Background: This study aims to compare the cleaning effectiveness of the pulsed vacuum cleaning and disinfection machine (PVD) and the spraying cleaning and disinfection machine (SCD) in cleaning rigid endoscope instruments.

Methodology: A total of 900 postoperative rigid endoscope instruments from the sterilization supply room of our hospital, collected between July and December 2024, were included in the study. Instruments were randomly divided into two groups using a computer-generated random number sequence, ensuring a 1:1 allocation ratio: the research group (450 items) and the control group (450 items). The research group used the PVD machine, while the control group used the SCD machine. The sterilization effectiveness, cleaning quality, ATP bioluminescence assay, and protein residue measurement were compared between the two groups.

Results: The sterilization time in the research group was longer than that in the control group. The instrument damage rate and endotoxin positive rate were significantly lower in the research group ($p < 0.05$). The research group showed significantly higher results in the paper test method compared to the control group ($p < 0.05$). No significant difference was found between the two groups in visual inspection and blood residue comparison ($p > 0.05$). The ATP bioluminescence detection and protein residue pass rates were higher in the research group than in the control group, with a statistically significant difference ($p < 0.05$).

Conclusions: The pulsed vacuum cleaning and disinfection machine performs better than the spraying cleaning and disinfection machine in cleaning rigid endoscope instruments, offering potential benefits for patient safety and instrument longevity.

Key words: Pulsed vacuum cleaning and disinfection machine; spraying cleaning and disinfection machine; rigid endoscope instruments; cleaning.

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Introduction

With the rapid development of medical technology, endoscopic instruments have become an essential part of many surgical procedures. Rigid endoscopes, in particular, are critical in minimally invasive surgeries, directly interacting with the human body and often coming into contact with blood, pus, and pathological tissues [1,2]. These instruments, after use, typically retain biological contaminants such as blood, pus, and proteins. If they are not thoroughly cleaned, harmful bacteria can remain on the instrument's surface, leading to cross-contamination or hospital-acquired infections (HAIs) when reused. Therefore, effective cleaning and disinfection of these instruments is crucial to prevent such infections and safeguard patient health.

Cleaning and sterilization of rigid endoscopes are essential steps in ensuring their safety and efficacy. Incomplete cleaning or sterilization can lead to the retention of organic residues on the instruments. These residues can interfere with the disinfectant's ability to contact the instrument's surface, contributing to the formation of biofilms that hinder the penetration of sterilizing agents like steam. Biofilms also enhance microbial resistance to heat, ultimately reducing the quality of sterilization and increasing the risk of infections [3,4]. Hence, improving the cleaning quality of rigid endoscope instruments is of utmost importance in reducing hospital infection rates and ensuring patient safety.

Currently, the cleaning of rigid endoscope instruments is often performed based on individual experience without standardized, uniform procedures [5]. This highlights the need for an effective, reliable cleaning method. Among the various cleaning methods, the pulsed vacuum cleaning and disinfection machine (PVD) and the spraying cleaning and disinfection machine (SCD) are the two most commonly used devices in hospital sterilization supply rooms. Both machines have their respective advantages [6,7]. The SCD machine is favored for its short cycle time and low energy consumption [8], while the PVD machine excels in cleaning instruments with lumens or hollow spaces, which the SCD machine cannot effectively handle [9].

Both devices have been shown to achieve cleaning

pass rates of over 98% when used with general surgical instruments. However, when it comes to cleaning endoscopic instruments, the PVD machine has been found to outperform the SCD machine in terms of cleanliness. Despite this, there is limited research comparing the effectiveness of these two cleaning methods specifically for rigid endoscope instruments. This study aims to address this gap by investigating the comparative cleaning effectiveness of the PVD and SCD machines for rigid endoscope instruments.

Methodology

General Information

A total of 900 postoperative rigid endoscope instruments from the sterilization supply room of our hospital, collected between July and December 2024, were included in the study. After pretreatment, the instruments were allocated to one of the two groups using a computer-generated random number sequence, ensuring a 1:1 assignment ratio, resulting in the control group and the observation group, with 450 instruments in each group. The observation group consisted of 154 laparoscopes, 102 hysteroscopes, 67 arthroscopes, 51 nephroscopes, 45 prostate electrosurgical scopes, and 31 thoracoscopes. The contamination levels were classified as mild (291 instruments), moderate (108 instruments), and severe (51 instruments). The usage frequencies were ≤ 1 time/month (121 instruments), 2–5 times/month (258 instruments), and ≥ 6 times/month (71 instruments). The control group consisted of 132 laparoscopes, 108 hysteroscopes, 81 arthroscopes, 49 nephroscopes, 46 prostate electrosurgical scopes, and 34 thoracoscopes. The contamination levels were mild (296 instruments), moderate (108 instruments), and severe (46 instruments). The usage frequencies were ≤ 1 time/month (114 instruments), 2–5 times/month (251 instruments), and ≥ 6 times/month (85 instruments). There were no statistically significant differences between the two groups in terms of the types of rigid endoscope instruments, contamination levels, or usage frequencies ($p > 0.05$).

Both groups were managed by the same 14 staff members from the sterilization supply center, consisting of 1 male and 13 female staff members. The staff members' ages ranged from 33 to 54 years, with an average age of (43.85 ± 5.45) years, and their years of work experience ranged from 3 to 32 years, with an average of (27.09 ± 2.87) years. The educational levels of the staff included 2 with vocational school education, 1 with high school education, and 11 with a bachelor's degree.

Inclusion and Exclusion Criteria

Inclusion Criteria

- The surgical instruments' basic components were intact without any damage.
- All instruments were rigid endoscopes (excluding endoscope lenses).
- The accessories of the rigid endoscope instruments were complete.

Exclusion Criteria

- Rigid endoscope instruments with damage or those exceeding their service life.
- Non-rigid endoscope instruments.
- Rigid endoscope instruments with poor performance.

Methods

Instrument Pretreatment

Related personnel performed personal protective measures, including wearing masks, hats, and rubber gloves to avoid injury from surgical instruments and reduce the risk of cross-infection during cleaning.

Rigid endoscopes were categorized as either dismountable or non-dismountable. Dismountable instruments were disassembled into their smallest units before being cleaned to ensure cleaning quality. The disassembled instruments were first soaked in an enzymatic solution for 10 minutes, then brushed with a brush to remove large blood stains from the inner surfaces. After brushing, the instruments were grouped and set aside for further processing.

Control Group

The control group used the spraying, cleaning, and disinfection machine. The cleaning process consisted of:

- Pre-wash for 2 minutes
- Enzyme wash for 10 minutes
- Rinsing for 2 minutes
- Second rinse for 1 minute
- Final rinse for 15 minutes
- Drying for 15 minutes after final rinsing.

Observation Group

The observation group used the pulsed vacuum cleaning and disinfection machine. After pre-cleaning, the instruments were placed on a specialized cleaning rack for endoscopes. Each batch could hold up to 15 instruments. The cleaning process involved:

- Pre-cleaning for 1 minute
- Main cleaning for 5 minutes
- Rinsing for 2 minutes

- Hot rinsing for 2 minutes
- Final rinsing for 3 minutes
- Disinfection for 3 minutes
- Drying for 20 minutes.

The cleaning and disinfection machine used was an automatic model (PC-150L, Shandong Xinhua Medical Equipment Co., Ltd.).

Observational Indicators

Sterilization Effectiveness Indicators: The sterilization time, instrument damage rate, and endotoxin positive rate were statistically analyzed for both groups.

Cleaning Quality: After cleaning and disinfection, the cleaning quality of the rigid endoscope instruments was assessed using the following methods:

Paper Test: A paper test strip was dipped into the residual moisture on the instrument. The color change in the paper was observed within 1 minute under non-light conditions. If the test paper turned light green or green in part or in whole, it was considered positive, indicating the presence of residual alkaline or acidic substances and thus a cleaning failure (not qualified). Absence of such a color change meant the test was negative and the cleaning was considered qualified. The 'qualification rate' for this test refers to the percentage of instruments deemed qualified.

Visual Inspection: The instruments were inspected with a magnifying glass for visible dirt or blood residues on areas such as the teeth, joints, and lumens. Instruments with no visible residues were considered qualified.

Residual Blood Test: The instruments were subjected to an OB test. The lumen, joints, teeth, and surface were wiped with a cotton ball, then 2 drops each of Solution A and Solution B were applied to the cotton ball. The color change of the cotton ball was observed. A purple-red or purple-blue color indicated a positive result, meaning the cleaning did not meet standards. No color change indicated a negative result, meaning the cleaning met standards (qualified). The 'qualification rate' for this test refers to the percentage of instruments deemed qualified.

ATP Bioluminescence Detection

The cleaning effectiveness was evaluated using ATP bioluminescence detection. According to the manufacturer's instructions, the threshold values for different instrument types were used to monitor and evaluate the cleaning effectiveness of surgical instruments:

For lumen instruments (e.g., endoscope aspirators), the cleaning was considered negative and qualified if ≤ 200 RLU.

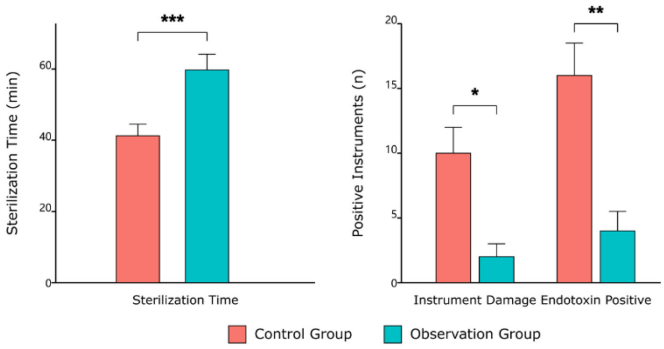
For surface instruments (e.g., endoscopic vascular forceps), the cleaning was considered negative and qualified if ≤ 150 RLU.

The 'qualification rate' for this test refers to the percentage of instruments deemed qualified based on these criteria.

Protein Residue Measurement

A swab was moistened with two drops of wetting solution and applied pressure while rotating it across the surface, joints, and gaps of the instruments. The swab was then placed into a test stick, and the reaction solution was activated. The swab was lifted and shaken

Figure 1. Comparison of sterilization effectiveness between observation and control groups.



The observation group demonstrated a significantly longer sterilization time but lower instrument damage rate and endotoxin positive rate compared to the control group. Asterisk (*) indicates statistically significant differences ($p < 0.05$).

Table 1. Comparison of sterilization effectiveness between the two groups.

Group	Sterilization Time (min)	Instrument Damage Rate [n (%)]	Instrument Endotoxin Positive Rate [n (%)]	Effect Size / 95% CI	t/χ^2	*p*
Observation Group (n = 450)	56.39 ± 4.32	2 (0.44%)	4 (0.89%)	Time: Mean Diff 18.15 (17.65, 18.65) min, Damage: OR 0.20 (0.04, 0.90), Endotoxin: OR 0.24 (0.08, 0.73)	-71.538	< 0.001
Control Group (n = 450)	38.24 ± 3.21	10 (2.22%)	16 (3.56%)		Damage: 5.405, Endotoxin: 7.364	Damage: 0.020, Endotoxin: 0.007

ORs are for Observation Group vs. Control Group. For Sterilization Time, t = -71.538, $p < 0.001$. For Damage Rate, $\chi^2 = 5.405$, $p = 0.020$. For Endotoxin Positive Rate, $\chi^2 = 7.364$, $p = 0.007$.

Table 2. Comparison of Cleaning Quality between the Two Groups.

Group	Paper Test Qualified [n(%)]	Visual Inspection Qualified [n(%)]	Residual Blood Qualified [n(%)]	OR (95% CI) for Qualification	χ^2	*p*
Observation Group (n = 450)	439 (97.56%)	445 (98.89%)	442 (98.22%)	Paper Test: 3.16 (1.57, 6.32)	11.565 (Paper)	0.001 (Paper)
Control Group (n = 450)	417 (92.67%)	447 (99.33%)	446 (99.11%)	Visual Insp.: N/A ($p > 0.05$), Resid. Blood: N/A ($p > 0.05$)	0.504 (Visual)	0.478 (Visual)
				1.351 (Blood)	0.245 (Blood)	

OR is for Observation Group vs. Control Group being qualified. N/A (Not Applicable) where p > 0.05. χ^2 and p are from Chi-square tests for each outcome.

until it turned green. After 15 seconds of shaking, the test stick was removed to maintain the swab's contact with the reaction solution. After the test stick was heated to 60°C, the protein residue was measured. A protein residue of < 1 μg was considered qualified. The 'qualification rate' for this test refers to the percentage of instruments deemed qualified.

Statistical Analysis

SPSS 26.0 software was used for statistical analysis. Normally distributed data were described using mean ± standard deviation (x ± s) and analyzed using t-tests; for significant differences, the 95% confidence interval (CI) for the mean difference was also reported. Non-normally distributed data were described using the median and interquartile range (M (Q1–Q3)) and analyzed using rank sum tests. Count data were described using frequency (percentage) and analyzed using chi-square tests for unordered data, and rank sum tests for ordered data; for significant differences in proportions, odds ratios (OR) with 95% CIs were calculated. A *p* of < 0.05 was considered statistically significant.

Results

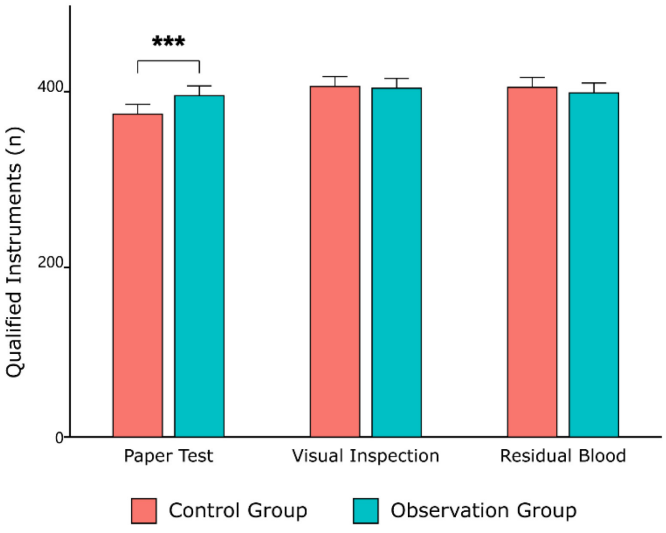
Comparison of Sterilization Effectiveness between the Two Groups

The sterilization time in the observation group was significantly longer than that in the control group (mean difference: 18.15 min, 95% CI [17.65, 18.65]). The instrument damage rate (OR 0.20, 95% CI [0.04, 0.90] for observation vs. control) and the endotoxin positive rate (OR 0.24, 95% CI [0.08, 0.73] for observation vs. control) in the observation group were lower than those in the control group, with statistically significant differences ($p < 0.05$), as shown in Table 1 and Figure 1.

Comparison of Cleaning Quality between the Two Groups

The paper test method in the observation group showed a significantly higher qualification rate than the control group (OR for qualification 3.16, 95% CI [1.57, 6.32] for observation vs. control), with a statistically significant difference ($p < 0.05$). However, the visual inspection and residual blood tests between the two groups showed no significant difference ($p > 0.05$), as shown in Table 2 and Figure 2.

Figure 2. Cleaning quality assessment between groups using different evaluation methods.



While the observation group showed a significantly higher qualification rate in the paper test method compared to the control group, no significant differences were observed in visual inspection or residual blood tests. Asterisk (*) denotes statistical significance (p < 0.05).

Table 3. Comparison of ATP Bioluminescence Detection and Protein Residue between the Two Groups.

Group	ATP Bioluminescence Detection Qualified [n(%)]	Protein Residue Qualified [n(%)]	OR (95% CI) for Qualification	χ^2	*p*
Observation Group (n = 450)	437 (97.11%)	439 (97.56%)	ATP: 2.23 (1.14, 4.36), Protein: 2.55 (1.25, 5.20)	5.750 (ATP)	0.016 (ATP)
Control Group (n = 450)	422 (93.78%)	423 (94.00%)		7.034 (Protein)	0.008 (Protein)

OR is for Observation Group vs. Control Group being qualified. χ^2 and p are from Chi-square tests for each outcome.

Comparison of ATP Bioluminescence Detection and Protein Residue between the Two Groups

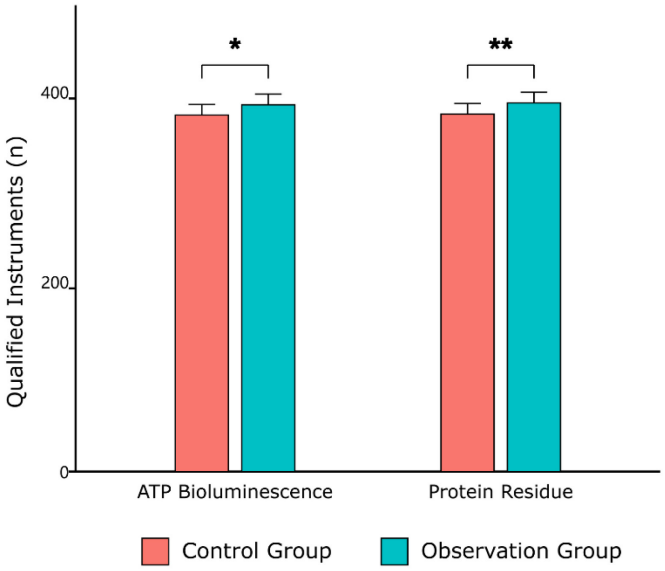
The observation group showed a significantly higher qualification rate for both ATP bioluminescence detection (OR for qualification 2.23, 95% CI [1.14, 4.36] for observation vs. control) and protein residue testing (OR for qualification 2.55, 95% CI [1.25, 5.20] for observation vs. control) compared to the control group, with statistically significant differences ($p < 0.05$), as shown in Table 3 and Figure 3.

Discussion

Numerous infection management guidelines in healthcare institutions indicate that all rigid endoscope instruments must be thoroughly cleaned and sterilized after use. Any organic matter left on the surface of rigid endoscope instruments can potentially affect the penetration of disinfectants and sterilizing agents, ultimately influencing the sterilization effectiveness. Therefore, the cleaning process for rigid endoscope instruments is crucial in the entire disinfection and sterilization procedure. The thoroughness of cleaning directly correlates with the effectiveness of disinfection and sterilization [10]. Cleaning of rigid endoscope instruments is often the key factor in determining the quality of disinfection and sterilization. Only by ensuring proper cleaning can one effectively guarantee that rigid endoscope instruments are free of toxins, bacteria, and pyrogens, thereby controlling hospital-acquired infection rates. Zheng *et al.* [11] indicated that sterilization and disinfection are the most critical aspects of infection control. Effective disinfection and sterilization can significantly improve the cleaning quality of medical instruments. Nabeel *et al.* [12] pointed out that effective cleaning methods could significantly improve the cleaning quality of surgical instruments. Sheng *et al.* [13] found that automated cleaning machines provided better cleaning results for surgical instruments before disinfection and are worth promoting. Stankiewicz *et al.* [14] highlighted that automated cleaning and disinfection machines effectively control infection during the post-processing of dental instruments. Yamashita *et al.* [15] concluded that cleaning and disinfection machines could significantly improve the cleaning effects of surgical instruments.

The results of this study showed that the sterilization time in the observation group was longer than in the control group, and the instrument damage rate and endotoxin positive rate were lower in the observation group ($p < 0.05$). This suggests that the pulsating vacuum cleaning and disinfection machine

Figure 3. ATP bioluminescence and protein residue qualification rates in both groups.



The observation group exhibited significantly higher qualification rates in both ATP bioluminescence detection and protein residue testing compared to the control group. Asterisk (*) indicates statistically significant differences ($p < 0.05$).

can effectively reduce the instrument damage rate and endotoxin positive rate for rigid endoscope instruments, although it requires a longer sterilization time. The clinical implication of a lower instrument damage rate is significant, potentially leading to reduced repair and replacement costs and ensuring the availability of critical instruments. More importantly, a lower endotoxin positive rate directly contributes to patient safety by minimizing the risk of postoperative pyrogenic reactions and infections associated with residual endotoxins on surgical instruments [16]. Endotoxins, components of Gram-negative bacteria's cell walls, can cause severe inflammatory responses if introduced into the bloodstream or sterile body sites [17]. This is mainly because the pulsating vacuum cleaning and disinfection machine is primarily designed for sterilization. It uses a vacuum pump to repeatedly evacuate and reintroduce air, generating pulsating airflow that expels cold air and allows steam to fully contact the items, achieving thorough sterilization. Its cleaning and disinfection process is more complex, involving multiple steps such as vacuuming, air intake, heating, sterilization, and drying. For example, a typical three-pulse vacuum sterilization process may take approximately 40-60 minutes. In contrast, the spraying, cleaning, and disinfection machine uses high-pressure nozzles to spray cleaning solutions and hot water onto

the rigid endoscope for washing and disinfection. This process typically includes pre-washing, main washing, rinsing, and disinfection, with relatively shorter time intervals: pre-washing (2-3 minutes), main washing (3-5 minutes), rinsing (2-3 minutes), disinfection (5-10 minutes), and other auxiliary times. As a result, the entire cleaning and disinfection process usually lasts 15-30 minutes.

Liu *et al.* [18] found that pulsating vacuum cleaning and disinfection machines can effectively improve the cleaning quality of dental instruments and shorten cleaning time. The results of this study showed that the paper test qualification rate in the observation group was higher than in the control group ($p < 0.05$), while there were no significant differences in visual inspection or residual blood comparison ($p > 0.05$). This suggests that the pulsating vacuum cleaning and disinfection machine can effectively improve the cleaning quality of rigid endoscope instruments, consistent with the findings of the aforementioned studies. The pulsating vacuum cleaning and disinfection machine uses a vacuum pump to generate pulsating airflow that expels cold air, allowing steam to contact all parts of the rigid endoscope. This process can effectively remove stubborn stains and microorganisms from hidden and hard-to-clean areas such as the endoscope's lumen, gaps, and joints, especially for organic matter like proteins and blood adhering to the endoscope surface. However, its limitation lies in its primary function of sterilization; while it has some cleaning ability, it is not as effective as the spraying cleaning and disinfection machine for removing large particles of dirt or dried stains on the surface.

On the other hand, the spraying cleaning and disinfection machine sprays cleaning liquid with high pressure and from multiple angles, generating strong mechanical scrubbing forces that can quickly and effectively remove visible contaminants like dust, blood, and mucus from the rigid endoscope surface. For oily stains on the surface, the surfactants in the cleaning solution can emulsify and remove them, effectively cleaning the surface in a short period. Its limitations include potential blind spots in deep internal areas or complex structures of the endoscope, where the spray may not reach, thus affecting cleaning effectiveness. Additionally, if the cleaning solution's concentration, temperature, or spray pressure is improperly set, cleaning may not be thorough [19].

Luo *et al.* [19] found that the pulsating vacuum cleaning and disinfection machine has a higher cleaning qualification rate than the spraying cleaning and disinfection machine when processing surgical instruments. However, when processing endoscopic instruments, the pulsating vacuum cleaning and disinfection machine showed a higher qualification rate compared to the spraying cleaning and disinfection machine. In this study, the ATP bioluminescence detection and protein residue qualification rates in the observation group were higher than in the control group ($p < 0.05$), indicating that the pulsating vacuum cleaning and disinfection machine can effectively improve the ATP bioluminescence detection and protein residue qualification rates for rigid endoscope instruments. This is because, in the cleaning process, initial cleaning is performed to remove more obvious stains, and then the instruments are placed into the pulsating vacuum cleaning and disinfection machine, effectively cleaning difficult-to-reach areas like instrument gaps and grooves, thereby improving the cleaning quality. After that, the full-automatic spraying, cleaning, and disinfection machine is used for a second cleaning to effectively remove contaminants, improving the ATP bioluminescence detection and protein residue qualification rates, and enhancing the overall cleaning quality.

In summary, both pulsating vacuum cleaning and disinfection machines and spraying cleaning and disinfection machines can be used for rigid endoscope instruments. The pulsating vacuum cleaning and disinfection machine can effectively reduce the instrument damage rate and endotoxin positive rate, but requires a longer sterilization time. It also improves ATP bioluminescence detection and protein residue qualification rates, thus enhancing cleaning quality. These findings have important clinical implications. The enhanced cleaning efficacy, particularly the reduction in endotoxin levels and protein residues achieved by the PVD machine, translates to a lower risk of surgical site infections and other HAIs, directly benefiting patient outcomes [17]. While the PVD machine has a longer cycle time, the trade-off for superior cleaning and reduced instrument damage may be justifiable in settings where patient safety and instrument longevity are paramount. The reduced damage rate also implies cost savings over time by extending the lifespan of expensive rigid endoscopes. Meanwhile, the spraying, cleaning, and disinfection machine has a shorter cleaning time but may have limitations in cleaning deep internal areas or complex structures of the endoscope. Healthcare facilities should weigh these factors—cleaning efficacy, cycle time, instrument compatibility, and cost-effectiveness—when selecting an automated cleaning system for rigid

endoscopes to ensure optimal patient care and resource management.

Ethics approval and consent to participate

The study protocol was approved by the Ethics Committee of Shijiazhuang Maternal and Child Health Hospital, and the study was performed in accordance with the Helsinki II declaration. Informed consent was obtained from all the study subjects before enrollment.

Availability of data and material

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

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Authors' contributions

JL and YH contributed to the conception and design of the study. All authors participated in the clinical practice, including diagnosis, treatment, consultation, and follow-up of patients. LB and XW contributed to the acquisition of data. JL, WH, and XW contributed to the analysis of data. JL wrote the manuscript. YH revised the manuscript. All authors approved the final version of the manuscript.

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Conflict of interest

No conflict of interest is declared.

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