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INDIVIDUALIZED SOFTWARE-ASSISTED TROCAR PLACEMENT FOR LAPAROSCOPIC APPENDECTOMY IN ACUTE APPENDICITIS: A RETROSPECTIVE-PROSPECTIVE COHORT STUDY

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Background: Technically difficult acute appendicitis remains a major challenge in emergency laparoscopy. Retrocecal or retroperitoneal appendiceal position, inflammatory adhesions, periappendiceal abscess, peritonitis, obesity, and insufficient instrument reach may compromise exposure and increase the likelihood of conversion. This study assessed whether individualized software-assisted trocar-placement planning, supported by intraoperative geometric verification and adjunctive argon plasma coagulation (APC) of the appendiceal stump, was associated with improved technical and early clinical outcomes.

Methods: This single-center retrospective-prospective observational cohort study included 196 adults who underwent laparoscopic appendectomy for acute appendicitis between January 2021 and April 2026. The control group comprised 115 patients treated with conventional trocar placement, whereas the main group comprised 81 consecutive patients treated using individualized trocar planning with the “Laparoscopic appendectomy” software, intraoperative verification with an endoscopic protractor-goniometer, and APC of the appendiceal stump. Baseline characteristics, access-related technical difficulties, trocar repositioning, conversion, postoperative complications, operative time, and hospital stay were compared between groups.

Results: Baseline demographic, clinical, BMI, inflammatory-form, time-to-admission, and peritonitis-severity distributions were comparable between groups. The main group had a lower conversion rate than the control group (2/81 [2.5%] vs 36/115 [31.3%]; $p < 0.001$), fewer postoperative complications (1/81 [1.2%] vs 19/115 [16.5%]; $p < 0.001$), and no repeated trocar repositioning compared with 29/115 patients (25.2%) in the control group. Use of an additional fourth trocar was also lower in the main group (14/81 [17.3%] vs 29/115 [25.2%]). Mean postoperative hospital stay decreased from 4.7 ± 1.3 to 3.2 ± 1.5 days. In a pilot microbiological subgroup, APC-treated stump cultures showed no microbial growth, whereas residual contamination persisted after monopolar coagulation.

Conclusions: Individualized geometric trocar planning with software support and intraoperative angle verification was associated with fewer conversions, fewer access-related technical difficulties, and improved early postoperative outcomes in laparoscopic appendectomy for acute appendicitis. The method provides a reproducible framework for precision port placement and may be useful for surgical training. Because the study was non-randomized and single-center, external validation in prospective multicenter trials is required.

Keywords: acute appendicitis; laparoscopic appendectomy; trocar placement; surgical ergonomics; geometric modeling; endoscopic protractor; argon plasma coagulation.

INTRODUCTION

Acute appendicitis remains one of the most common surgical emergencies worldwide, and laparoscopic appendectomy is considered the preferred operative approach because it is associated with less postoperative pain, shorter hospital stays, faster recovery, and fewer wound complications than open surgery. Nevertheless, technically demanding cases remain a major challenge, particularly in patients with obesity, retrocecal or retroperitoneal appendix location, inflammatory infiltrates, periappendiceal abscess, or diffuse peritonitis [2, 6, 21, 31].

Recent studies have highlighted the importance of surgical ergonomics and personalized minimally invasive surgery; however, no clinically practical framework has combined anthropometric measurements, geometric modeling, estimated target-organ depth, and intraoperative verification into a reproducible method for individualized trocar planning. To address this gap, we developed a mathematical model, dedicated planning software, and an endoscopic protractor-goniometer [8, 14, 17, 24].

Emergency abdominal surgery remains a substantial contributor to morbidity, mortality, and healthcare resource use worldwide. Acute appendicitis is one of the most common urgent abdominal conditions requiring surgical treatment, and laparoscopic appendectomy is widely accepted as the preferred operative approach in suitable patients because it reduces surgical trauma, improves visualization, and supports faster recovery compared with open surgery [1, 5, 7, 15, 26, 29].

Despite the widespread adoption of laparoscopy, technically difficult acute appendicitis continues to present important operative challenges. Retrocecal or retroperitoneal appendiceal location, dense inflammatory adhesions, periappendiceal abscess, diffuse peritonitis, obesity, and limited instrument reach can compromise exposure and increase the risk of conversion. In these situations, trocar geometry is not a minor technical detail; it directly influences visualization, triangulation, instrument reach, tissue traction, and the ability to perform safe dissection [3, 4, 9, 23, 25, 32].

Conventional trocar maps are usually based on standard anatomical landmarks and the surgeon's experience. Although this approach is adequate in many routine cases, it may be less reliable when patient habitus, pneumoperitoneum-related abdominal-wall displacement, or atypical target-organ position changes the effective working distance and approach angle. A reproducible method that integrates anthropometric measurements, estimated target depth, inter-port distance, and ergonomic principles may therefore improve access planning in emergency laparoscopy [18, 20, 22, 24, 28].

The knowledge gap addressed in this study is the lack of a simple, clinically applicable, patient-specific method for objective trocar-placement planning in laparoscopic appendectomy. Most studies of appendectomy focus on the choice of operative approach, stump closure, infectious complications, or antibiotic treatment; fewer evaluate port placement as a measurable determinant of technical success. We therefore developed a geometric planning model, dedicated software, and an endoscopic protractor-goniometer for intraoperative verification of calculated access parameters [16, 19, 27, 30].

The objective of this study was to evaluate whether individualized software-assisted trocar-placement planning, supported by intraoperative geometric measurement and combined with APC of the appendiceal stump, was associated with improved technical and early clinical outcomes in patients undergoing laparoscopic appendectomy for acute appendicitis.

MATERIALS AND METHODS

This study analyzed 196 patients who underwent laparoscopic appendectomy for acute appendicitis in the Department of Emergency Surgery, Clinic No. 2 of Tashkent State Medical University, from January 2021 to April 2026. The control group included 115 patients treated between 2021 and 2024 using the conventional laparoscopic approach, and the main group

included 81 consecutive patients treated from 2024 to April 2026 using the proposed software-assisted trocar-placement strategy combined with APC.

Study design and ethics

This observational, non-randomized retrospective-prospective cohort study was conducted at the Department of Emergency Surgery, Clinic No. 2 of Tashkent State Medical University, between January 2021 and April 2026. The study protocol was approved by the Local Ethics Committee of Tashkent State Medical University (Protocol No. 15, dated 16 April 2026). Written informed consent was obtained from patients included prospectively; for the retrospective cohort, anonymized data were analyzed in accordance with institutional ethical requirements.

Inclusion and exclusion criteria

Inclusion criteria: patients aged 18–75 years with a verified diagnosis of acute appendicitis (catarrhal, phlegmonous, or gangrenous form) who underwent laparoscopic appendectomy.

Exclusion criteria were as follows: (1) suspected appendiceal neoplasm or another primary acute abdominal condition requiring a different surgical strategy; (2) diffuse peritonitis with septic shock; (3) severe uncorrected coagulopathy (platelet count $<50 \times 10^9/L$ or INR >1.5); (4) pregnancy; (5) previous extensive abdominal surgery associated with dense adhesions; and (6) refusal to participate.

Group allocation and sample-size calculation

Patients were allocated according to the treatment period using non-randomized consecutive sampling. The control group comprised 115 patients treated retrospectively between 2021 and 2024 using the standard laparoscopic approach. The main group comprised 81 consecutive patients treated prospectively between 2024 and April 2026 using the proposed software-assisted trocar-placement strategy combined with argon plasma coagulation. The sample-size calculation was performed in G*Power 3.1, assuming a reduction in conversion rate from 30% to 12%, with $\alpha = 0.05$ and 80% power. The minimum required sample size was 68 patients per group; therefore, the available sample was considered adequate for the primary comparison.

Surgeon experience

All laparoscopic procedures in both groups were performed or directly supervised by the same experienced surgeon (M.Sh. Khakimov, Professor; >39 years of surgical experience and 289 laparoscopic appendectomies). The assisting surgeons had comparable levels of training, which reduced performance-related variability between groups.

Interventions

Control group: standard three-trocar laparoscopic appendectomy with monopolar coagulation for hemostasis.

Main group: laparoscopic appendectomy with individualized trocar placement based on the “Laparoscopic appendectomy” software, followed by intraoperative argon plasma coagulation of the appendiceal stump.

Statistical analysis

Statistical analysis was performed using IBM SPSS Statistics, version 26.0. The Shapiro–Wilk test was used to assess normality. Normally distributed continuous variables are reported as mean $\pm$ standard deviation, whereas non-normally distributed variables are reported as median and interquartile range. Categorical variables are presented as absolute numbers and percentages. Between-group comparisons were performed using Student’s t-test, the Mann–Whitney U test, the chi-square test, or Fisher’s exact test, as appropriate. Logistic regression analysis was used to identify independent predictors of conversion to open surgery. Odds ratios (ORs) with 95%

confidence intervals (CIs) were calculated. A two-sided p-value <0.05 was considered statistically significant.

Because treatment allocation was based on the treatment period rather than randomization, between-group differences were interpreted as associations. This design limitation was considered when interpreting the effect of the intervention on conversion and postoperative outcomes.

Baseline characteristics of patients with acute appendicitis were summarized before outcome analysis. Age categories were defined according to commonly used clinical age groups: young adults (<45 years), middle-aged adults (45-59 years), elderly patients (60-74 years), and patients aged 75 years or older (Table 1).

Table 1

Distribution of patients by sex and age in acute appendicitis (n = 196)

Age	Men		Women		Total	Overall p-value
	control group	main group	control group	main group		Overall p-value
18-44 years	56	42	31	21	150 (76.5%)	p>0.05
45-59 years	15	11	9	5	40 (20.4%)	p>0.05
60-74 years	3	2	1	0	6 (3.1%)	p>0.05
75 and above years	-	-	-	-	-	p>0.05
Total	74 (37.8%)	55 (28%)	41 (20.9%)	26 (13.3%)	196 (100%)	p>0.05
						p>0.05

Patients were 18-74 years old, with a mean age of 29 ± 3.5 years. Overall, 129 patients (65.8%) were men and 67 (34.2%) were women. Most patients (150/196; 76.5%) were younger than 45 years, indicating that acute appendicitis predominantly affected working-age adults in the present cohort. Baseline age and sex distributions were comparable between the control and main groups.

Comorbid conditions were recorded to assess baseline clinical comparability. Because the cohort was predominantly young, the overall frequency of clinically relevant comorbidities was relatively low (Table 2).

Table 2.

Distribution of patients according to comorbidities

Comorbidity	Control		Main		p-value
	n	%	n	%	Overall p-value
Ischemic heart	9	7.8%	5	6.2%	p>0.05
Arterial	15	13	7	8.6	p>0.05

hypertension		%		%	
Peptic ulcer disease	27	23.5%	13	16%	p>0.05
Chronic hepatitis	4	3.5%	1	1.2%	p>0.05
Diabetes mellitus	6	5.2%	2	2.5%	p>0.05
Kidney diseases	9	7.8%	8	9.9%	p>0.05
Abdominal adhesions	6	5.2%	3	3.7%	p>0.05
Other diseases	4	3.5%	4	4.9%	p>0.05

As shown in Table 2, the distribution of comorbidities was similar between the two study groups, supporting acceptable baseline clinical comparability for the subsequent analysis.

Because the clinical course and technical complexity of laparoscopic appendectomy may vary depending on patient-related and disease-related factors, the following sections provide a more detailed description of the clinical material.

Table 3.

Distribution of patients according to body mass index (BMI) category

BMI	Control	Main	Total	p-value
16-18.5	16 (13.9%)	8 (9.9%)	24 (12.2%)	p = 0.74
18.5-24.9	41 (35.7%)	32 (39.5%)	73 (37.2%)	p=0.74
25.0-29.9	29 (25.2%)	22 (27.2%)	51 (26%)	p=0.74
30.0-34.9	18 (15.7%)	12 (14.8%)	30 (15.3%)	p=0.74
35.0-39.9	11 (9.6%)	7 (8.6%)	18 (9.2%)	p=0.74
Total	115	81	196	p=0.74

Body mass index is an important patient-related factor that may influence operative exposure, trocar reach, and surgical ergonomics. As shown in Table 3, BMI distribution was similar in the control and main groups. In the control group, 29 patients (25.2%) were overweight (BMI 25.0–29.9 kg/m²), 18 (15.7%) had class I obesity (BMI 30.0–34.9 kg/m²), and 11 (9.6%) had class II obesity (BMI 35.0–39.9 kg/m²). In the main group, 22 patients (27.2%) were overweight, 12 (14.8%) had class I obesity, and 7 (8.6%) had class II obesity.

Table 4.

Distribution of patients according to the inflammatory form of appendicitis

Inflammatory form of appendicitis	Control group	Main group	Total	p-value
Catarrhal	31 (27%)	22 (27.2%)	53 (27%)	p = 0.62
Phlegmonous	65 (56.5%)	49 (60.5%)	114 (58.2%)	p = 0.62

Gangrenous	19 (16.5%)	10 (12.3%)	29 (14.8%)	p = 0.62
Total	115	81	196	p = 0.62

Table 5.

Distribution of patients according to time from symptom onset to hospital admission

Time to hospital admission	Control		Main		Total		Overall p-value
	n	%	n	%	n	%	p = 0.996
Within 6 hours	22	19.1%	14	17.3%	36	18.4%	p = 0.996
From 6-12 hours	37	32.2%	27	33.3%	64	32.7%	p = 0.996
From 12-24 hours	26	22.6%	19	23.5%	45	23%	p = 0.996
From 24-48 hours	19	16.5%	14	17.3%	33	16.8%	p = 0.996
From 48-72 hours	11	9.6%	7	8.6%	18	9.2%	p = 0.996
Total	100%		100%		100%		p = 0.996

The inflammatory forms of appendicitis were similarly distributed between the control and main groups. Phlegmonous appendicitis was the most frequent form, occurring in 65 patients (56.5%) in the control group and 49 patients (60.5%) in the main group (Table 4). As shown in Table 5, most patients presented within the first 24 hours after symptom onset, accounting for approximately 74% of cases in both groups.

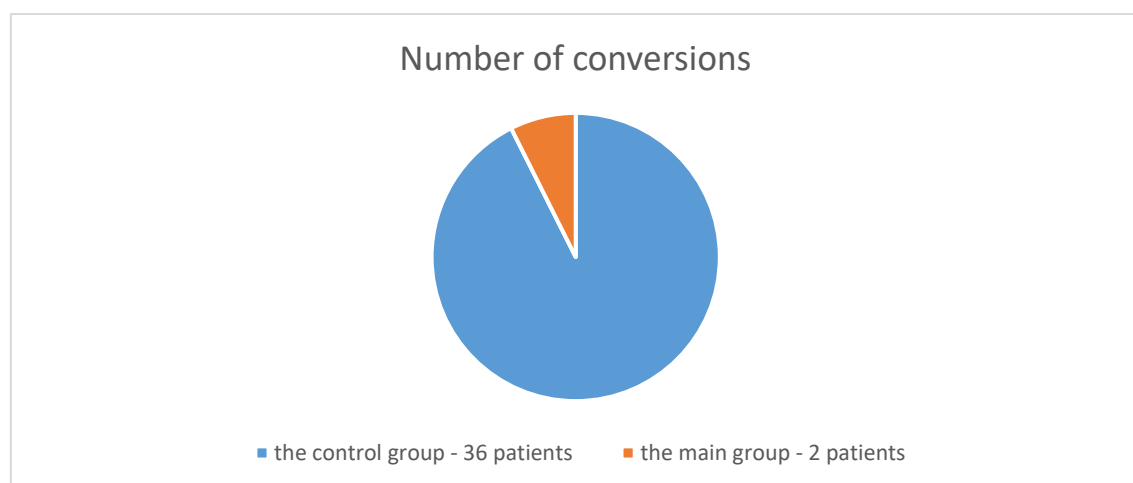


Figure 1. Conversion from laparoscopic appendectomy to open surgery in the control and main groups.

Table 6.

Distribution of peritonitis severity in patients with acute appendicitis

Form of peritonitis	Control		Main		Total		Overall p-value
	n	%	n	%	n	%	p = 0.931
Abscess	57	49.6%	39	48.1%	96	49%	p = 0.931
Local	36	31.3%	29	35.8%	65	33.2%	p = 0.931
Diffuse	18	15.6%	11	13.6%	29	14.8%	p = 0.931

Spilled	4	3.5%	3	3.7%	7	3.6%	p = 0.931
Total	100%		100%		100%		p = 0.931

Development of an endoscopic protractor-goniometer for objective trocar-access planning

In laparoscopic surgery, trocar entry sites and insertion angles are often selected on the basis of the surgeon's experience and visual estimation. The absence of a standardized tool for measuring insertion angles and inter-instrument distances may increase the risk of suboptimal access, impaired ergonomics, and injury to intra-abdominal organs or blood vessels.

We developed a novel endoscopic protractor-goniometer with an integrated linear measuring component (positive decision of the Intellectual Property Agency of the Republic of Uzbekistan, Decision No. IAP 8301). The device is designed as a circular disk with a circumferential angular scale and a sliding ruler, allowing simultaneous angular and linear measurements (Fig. 2).

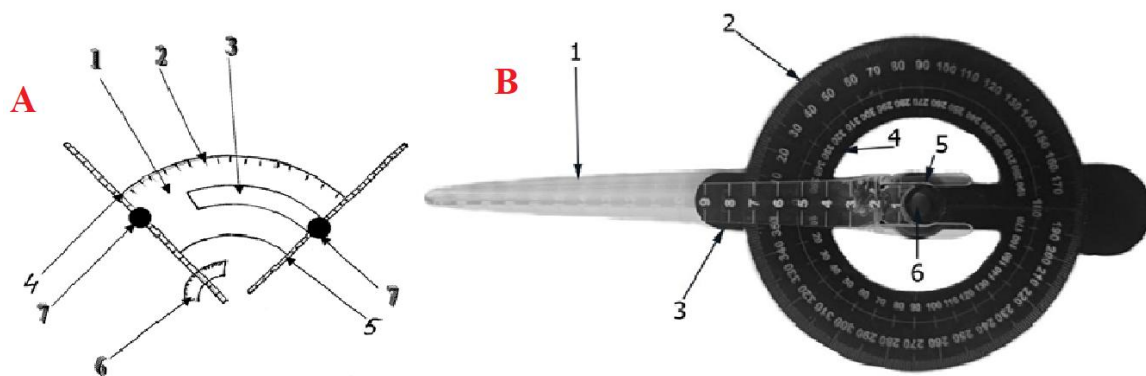


Figure 2. A – Schematic representation of the endoscopic protractor; B – endoscopic protractor with an integrated ruler. 1 – first component (ruler); 2 – second component (protractor); 3 – ruler scale for measuring length in centimeters; 4 – circular protractor scale (0–360°); 5 – ruler cutout for fixation to the first trocar; 6 – fixation point connecting the two components of the device and the first trocar.

Design Components:

1. Body: The device consists of a transparent medical-grade acrylic (polymethyl methacrylate) circular disk, predominantly blue, with a diameter of 120–130 mm. It is equipped with a circular goniometric scale (0–360°) with high-contrast graduations. The central part contains a through-hole for alignment with the intended trocar entry site.

2. Sliding ruler: This transparent acrylic component has a millimeter-scale graduation (0–200 mm). It allows measurement of inter-port distances, instrument insertion depth, and port-placement symmetry. The ruler can be securely locked in the selected position.

3. Additional reference guides: Lateral projections and cutouts along the disk periphery facilitate stable positioning on the patient's abdominal wall and alignment with anatomical landmarks [10, 11, 12, 13].

Material and Sterilization:

The device is fabricated from medical-grade acrylic (polymethyl methacrylate), which offers several distinct advantages:

High optical transparency, ensuring clear visualization of all scales.

Resistance to cold chemical disinfection (including alcohol-based and chlorine-based solutions).

Suitability for repeated clinical use.

Compatibility with steam autoclave sterilization (at up to 121°C and 1 atm), as well as with gas plasma and ethylene oxide sterilization methods.

Principle of Operation:

The device is placed on the anterior abdominal wall, and the central aperture is aligned with the intended access point. The protractor scale is used to determine the trocar insertion angle relative to the abdominal wall (for example, 45–60°). The sliding ruler allows accurate measurement of the distance between skin entry sites and assessment of port symmetry. When required, the device also helps determine the instrument approach angle relative to the target anatomical structure.

Technical Rationale and Clinical Value:

The device provides a standardized approach to laparoscopic port-site selection. Its use may improve the precision and safety of trocar insertion, reduce the risk of injury to vascular and parenchymal structures, and increase reproducibility of the surgical technique. It may also be useful for surgical training and simulation-based education.

Specific Features:

Integration of both angular (protractor) and linear (ruler) measurement functions within a single device.

A central aperture for precise anatomical landmark alignment.

Compatibility with both thermal (autoclave) and chemical sterilization methods.

Capacity for concurrent angular and distance measurements.

Uncomplicated design, facilitating ease of manufacture, handling, and maintenance.

Thus, the combined goniometer–linear measuring device represents a novel surgical instrument that integrates simple design, practical manufacturability, and potential clinical safety benefits.

Device Operating Principle

After induction of general anesthesia, creation of a carbon dioxide pneumoperitoneum, and insertion of a 30° laparoscope through a standard umbilical access point, the device is applied. The transparent sliding ruler, calibrated in millimeters, is used under direct visual control to measure the distance from the primary camera port to the planned site of the subsequent working port. The second entry point is then determined, and a fourth port site can be selected when clinically required.

The measured inter-port distances are then entered into the dedicated software program "Laparoscopic.exe." Additional patient-specific parameters are also entered, including height, weight, target-organ depth measured by preoperative ultrasonography, organ height, spatial coordinates of the proposed trocar sites relative to the operating table before and after pneumoperitoneum, and abdominal circumference.

Upon activation of the "CALCULATE" function, the software outputs the following parameters:

the recommended trocar insertion angle;

the optimal depth of instrument insertion through the trocar;

a qualitative grading of the calculated instrument insertion depth, categorized as excellent, good, satisfactory, unsatisfactory, or poor.

This grading system is based on the laparoscopic ergonomic principle that the distance between the trocar entry site and the operative field should approximate half the length of the working instrument, typically about 15 cm. The algorithm also incorporates accepted port-placement

criteria, including adequate inter-port angles, trocar insertion angles within the range of 40–65°, and inter-port distances of at least 5–8 cm.

Mathematical model

For laparoscopic appendectomy, the first trocar is usually introduced on or near the midline. The camera port should be positioned far enough from the target area to provide panoramic visualization, but close enough to allow safe visualization of all operative steps. During the procedure, the laparoscope should also be able to approach the most distant aspect of the target region when required.

In laparoscopic appendectomy, McBurney's point is an important anatomical and topographic landmark because it corresponds closely to the usual surface projection of the appendix base. It can therefore be used as a reference point for planning a spatial trocar configuration, which can be represented geometrically as a right triangle (Fig. 3).

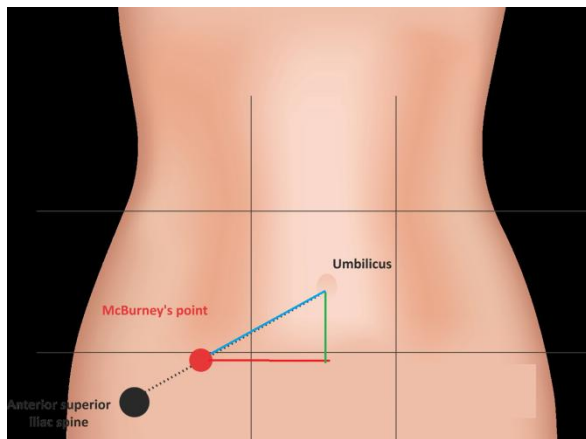


Figure 3. Schematic representation of right-triangle triangulation in laparoscopic appendectomy. Distance *a* denotes the distance from the midline to McBurney's point; distance *c* denotes the distance from the midline to the target organ. The value of *c* should not exceed the effective working length of the laparoscope.

When these two values are known, parameter *b* can be calculated using the Pythagorean theorem (Fig. 4). In a right triangle, the square of the hypotenuse is equal to the sum of the squares of the two legs. In this model, the hypotenuse corresponds to the effective working length of the laparoscope.

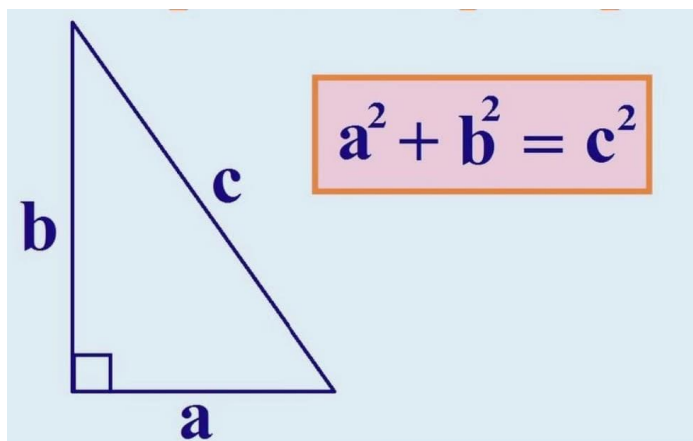


Figure 4. The Pythagorean theorem.

According to the principles of laparoscopic triangulation and ergonomic port placement, the instrument approach angle to the target organ should generally be maintained within a safe and efficient range of approximately 45°–75°.

The instrument shaft can be considered as a lever passing through a fulcrum at the level of the anterior abdominal wall:

at excessively low angles, friction and tension of the anterior abdominal wall increase because the instrument shaft runs almost parallel to the skin;

at excessively high angles, internal maneuverability decreases because the shaft becomes nearly perpendicular to the abdominal wall and the intracorporeal working cone narrows.

This ergonomic relationship may be described conceptually by an ergonomic-loss function $J(\alpha)$, where α is the instrument insertion angle. In this framework, small-angle penalties reflect increased abdominal-wall tenting and instrument sliding, whereas large-angle penalties reflect loss of intracorporeal working stroke and reduced maneuverability.

Because this function is intended to support planning rather than to serve as a validated universal equation, its parameters should be interpreted as adjustable weighting coefficients that require further validation in independent clinical cohorts.

Model interpretation:

$J(\alpha)$ represents the overall ergonomic loss associated with a given insertion angle; lower values indicate a more favorable balance between access safety and instrument maneuverability.

$\frac{1}{\sin \alpha}$ The small-angle component accounts for abdominal-wall tenting, instrument sliding, and external handle crowding.

$\frac{1}{\cos \alpha}$ The large-angle component accounts for reduced intracorporeal working stroke and loss of fine-motor control.

The relative weighting of these components depends on abdominal-wall thickness, target-organ depth, and the required operative maneuver; therefore, the model should be regarded as a patient-specific ergonomic planning framework.

Ergonomic interpretation:

if the angle is $<45^\circ$, the instruments become excessively parallel, increasing the risk of external hand collision and internal instrument conflict;

if the angle is $>75^\circ$, the instruments diverge excessively, which may reduce reach and increase tissue tension;

an angle close to 60° is generally considered ergonomically favorable because it provides adequate spatial separation while maintaining coordinated instrument movement toward the target.

In triangulation around the target, the camera forms the apex, while the working ports form the base. The instruments should converge toward the target without external hand collision or internal instrument crossing. Therefore, an approach angle of 45° – 75° , with a value close to 60° , is rational from the standpoint of laparoscopic ergonomics and technical efficiency.

$(\frac{S}{2D_{work}})\frac{\theta}{2}$ The angle between the axes of the two working instruments at the target point (T) was denoted by θ . If the working distances from the skin entry sites A and B to the target are approximately equal ($|AT| \approx |BT| = D_{work}$), triangle A-T-B can be considered isosceles. In this case, the inter-port distance S and target angle θ are related by the expression $S = 2 \times D_{work} \times \sin(\theta/2)$. Conversely, $\theta = 2 \times \arcsin[S/(2 \times D_{work})]$.

In this model, S represents the skin distance between the two working ports, D_{work} represents the distance from the trocar entry site to the target along the instrument axis, and θ represents the angle between the two working instruments at the target point.

For an optimal target angle of approximately 60° , $\sin(30^\circ) = 0.5$; therefore, under isosceles conditions, $S \approx D_{\text{work}}$. This provides a simple practical rule for estimating the desirable distance between working ports.

When the working distances are unequal, the same principle can be applied using the law of cosines: $S^2 = DA^2 + DB^2 - 2 \times DA \times DB \times \cos(\theta)$, where DA and DB are the working distances from ports A and B to the target.

The cutaneous distance between ports should therefore be selected not only by external landmarks, but also by the estimated intracorporeal working distance and the required approach angle.

$\frac{\theta}{2} \sqrt{(a - c)^2 + D^2} \sqrt{c^2 + D^2}$ If the depth of the appendix base is estimated by ultrasonography or computed tomography, the working distance from each trocar can be calculated using three-dimensional coordinates. This allows individualized preoperative or intraoperative verification of whether a planned port configuration provides sufficient reach and an ergonomically acceptable approach angle.

Thus, the proposed model should be regarded as a geometric planning tool rather than as a fixed universal rule. Its purpose is to support safer trocar placement by combining surface anatomy, estimated target depth, and ergonomic principles.

A target angle close to 60° represents an ergonomic compromise: the instruments are neither excessively parallel, which would reduce dissection efficiency and increase hand conflict, nor excessively divergent, which would impair precision and leverage.

Working distances were calculated using standard right-triangle relationships based on the measured horizontal distance from the port to the target projection and the estimated target depth.

$\sqrt{(a - c)^2 + D^2} \sqrt{c^2 + D^2} \frac{|TA| + |TB|}{2}$ For each trocar point, the working distance can be expressed as $D_{\text{work}} = \sqrt{(d^2 + h^2)}$, where d is the horizontal skin distance from the port to the target projection and h is the estimated vertical depth of the target.

The ideal inter-port distance for a given target angle can be estimated as follows:

$\frac{\theta}{2} S_{\text{ideal}} = 2 \times D_{\text{work}} \times \sin(\theta/2)$. For $\theta = 60^\circ$, $S_{\text{ideal}} \approx D_{\text{work}}$.

$\sum_i w_i \cdot d_i$ To account for the risk of excessive tension on the parietal peritoneum and adjacent intestinal loops, a penalty function may be introduced in which shorter unsafe distances to vulnerable structures receive greater weight.

In this conceptual model, d_i denotes the distance from the trocar trajectory to a vulnerable structure, and w_i denotes the relative clinical weight assigned to that structure.

Optimization techniques can then be used to identify trocar positions that minimize ergonomic loss while maintaining adequate safety margins from vulnerable structures.

Accordingly, optimal trocar sites can be selected by integrating triangulation principles, estimated target depth, patient habitus, and laparoscopic ergonomic constraints. This approach may improve technical feasibility and reduce access-related difficulties.

RESEARCH RESULTS

In the control group, all procedures were initiated as laparoscopic appendectomies under endotracheal general anesthesia. A 10-mm camera port was usually placed in the periumbilical region for insertion of a 30° laparoscope. Additional working ports were placed according to the conventional sector-based approach and the general principles of laparoscopic triangulation.

Pelvic drainage was not performed in 71 patients. Drainage of the pelvis and left paracolic gutter was performed in 16 cases when intraoperative contamination was judged clinically significant.

In several technically difficult cases, the standard access configuration was insufficient and had to be expanded; a fourth trocar was inserted in 29 patients (25.2%).

Review of the operative records showed that in 29 cases (25.2%) the position of a previously inserted trocar had to be corrected. The principal reason was insufficient instrument reach to the target area, which made mobilization of the appendix and safe dissection more difficult. Instrument interference, defined as crossing or restricted movement of instruments in the operative field, was documented in 7.8% of cases.

Conversion from laparoscopic appendectomy to open surgery was required in 36 patients (31.3%). Conversion was mainly associated with complex anatomical and inflammatory conditions that prevented safe completion of the operation laparoscopically. The most frequent causes included retrocecal or retroperitoneal appendiceal location, dense inflammatory adhesions, bleeding from mesoappendiceal vessels, periappendiceal abscess, and diffuse peritonitis.

Postoperative complications occurred in 19 patients (16.5%). Wound-related complications, including infiltration and suppuration at the access site, were the most common adverse events and were observed in 9 patients (7.8%). These complications were mainly associated with destructive appendicitis and marked intra-abdominal contamination. In 3 patients, wound suppuration progressed to fascial dehiscence with eventration. Five patients later developed incisional hernia during follow-up.

Postoperative hospital stay in the control group ranged from 2 to 7 days, with a mean duration of 4.7 ± 1.3 days.

The mean operative time in the control group was 68.2 ± 14.6 min.

In routine practice, the classical principles of triangulation could not always be achieved within standard port-placement zones. In several cases, the angle between working instruments deviated from the recommended ergonomic corridor of approximately 45° – 75° , which reduced maneuverability and complicated dissection.

Additional technical difficulties were related to instrument conflict, especially when instruments crossed within the abdominal cavity or were positioned too close to each other at the trocar channels. In obese patients, limited working length further reduced access to the target structures, sometimes requiring repositioning of one or more trocars.

Tactical and technical aspects of software-assisted laparoscopic appendectomy

To improve the technical performance of laparoscopic appendectomy and reduce access-related difficulties, we developed software for individualized planning of trocar entry sites, insertion angles, and working distances.

For computational analysis, a geometric model was created to represent the spatial relationship between the abdominal wall, trocar entry sites, and the target anatomical region (Fig. 5).

The program uses patient-specific anthropometric and intraoperative parameters to calculate the expected working distance and insertion angle for each trocar.

Point O represents the surface projection of the target region before carbon dioxide insufflation.

H = OL represents the estimated depth of the target organ from point O.

H₀ represents the vertical height of point O from the operating table before pneumoperitoneum.

H₁ represents the vertical height of the corresponding point after pneumoperitoneum.

H_A represents the vertical height of trocar entry point A from the operating table.

O_1A represents the distance from point A to the post-insufflation projection of the target region.

The following parameters were calculated:

AL: the estimated working distance from trocar point A to the target organ.

lambda: the insertion angle of the instrument introduced through trocar point A.

Definitions and computational relationships:

$O_1L = H + H_1 - H_0$, representing the estimated distance from the abdominal wall to the target after pneumoperitoneum.

$\Delta AM = H_1 - HA$, representing the vertical difference between the target projection and trocar entry point A.

$\sqrt{(AO)^2 - (AM)^2}$ MO_1 represents the horizontal component of the distance from trocar point A to the target projection.

AT was considered equivalent to MO_1 in the two-dimensional projection used for the initial calculation.

$\Delta TL = O_1L - HA$, representing the adjusted vertical component of the working distance.

$\sqrt{(AT)^2 - (TL)^2}$ The same calculation sequence was applied to trocar points B, C, and D.

Points B, C, and D were calculated using the same geometric algorithm.

$\frac{weight (kg)}{height (m)^2}$ Body mass index was calculated as BMI = weight (kg) / height² (m²).

$\frac{TL}{AT}$ The insertion angle was calculated as lambda = arctan(vertical component / horizontal component).

The calculated working distance was graded as follows:

15–19 cm: excellent;

20–24 cm: good;

25–29 cm: satisfactory;

30–34 cm: unsatisfactory;

≥35 cm: poor.

The distance between the trocar entry site and the operative field should approximate half the working length of the laparoscopic instrument, usually about 15 cm. This minimizes excessive external handle excursion, reduces the risk of uncontrolled intracorporeal movement, and improves instrument balance. From an ergonomic perspective, the surgeon's elbows should remain flexed at approximately 90°–120° to reduce fatigue during prolonged manipulation.

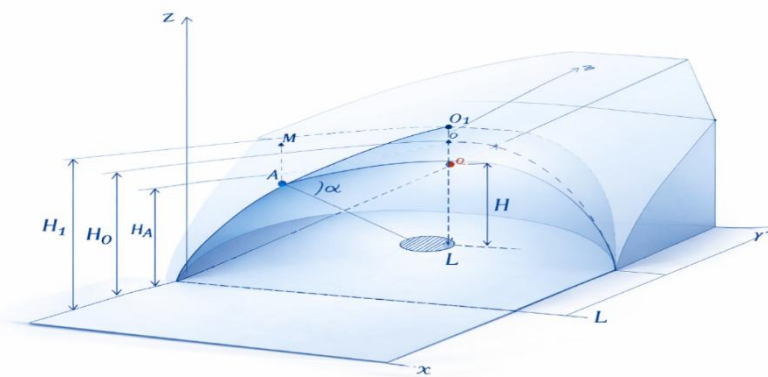
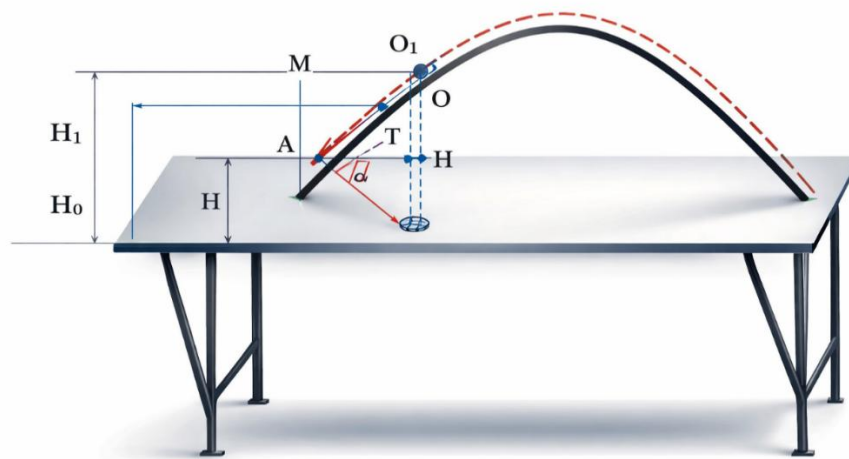


Figure 5. Geometric model of trocar placement and instrument trajectory in laparoscopic appendectomy.

Using this mathematical model, we developed the software program “Laparoscopic appendectomy,” which calculates optimal instrument-insertion parameters for laparoscopic appendectomy (Fig. 6). The program is registered with the Intellectual Property Agency of the Republic of Uzbekistan (No. DGU 62688).

Form1

The program for calculating the parameters of instrument insertion during laparoscopic appendectomy "Laparoscopic appendectomy"

last name first name patronymic		Height (cm)
		Weight (kg)
The height of the McBurney point from the operating table to the insufflation		
The depth of the cecum dome (by ultrasound) before insufflation		
The height of the McBurney point from the operating table after insufflation		
Abdominal circumference before insufflation		
Abdominal circumference after insufflation		

Point	The height of the standing point from the operating table after insufflation (cm)	Distance to McBurney Point (cm)
Point A		
Point B		
Point C		
Point D		

ACCOUNT EXIT

Figure 6. Interface of the “Laparoscopic appendectomy” software program.

Example calculation. In a patient with acute appendicitis and pre-obesity (BMI 28.7 kg/m²; height 170 cm; weight 83 kg), the pre-insufflation height of McBurney’s point from the operating table was 15 cm. The pre-insufflation depth of the cecal dome, measured by ultrasonography, was 9 cm (Fig. 7). After pneumoperitoneum, the height of McBurney’s point

increased to 17 cm. Abdominal circumference was measured at the epigastric, mesogastric, and hypogastric levels before and after insufflation and was entered into the software to individualize the calculations.

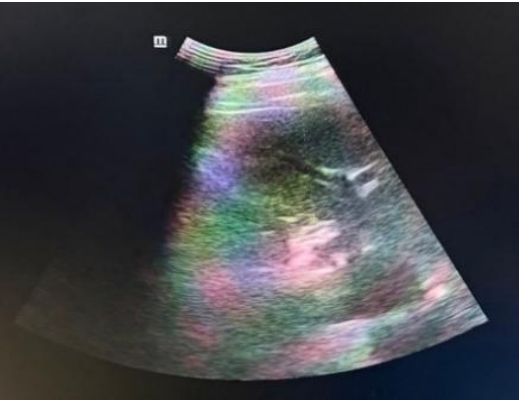


Figure 7. Ultrasonographic assessment of the depth of the appendix region.

For the BMI 25.0–29.9 kg/m² category, the calculated distance from camera port A to the cecal dome was 20.5 cm. Although this distance was classified as “good” according to the working-distance scale, it was considered functionally adequate because the camera port primarily provides visualization rather than direct tissue manipulation. The calculated working distance from port B to the cecal dome was 18.3 cm, with an approach angle of 49.1°; from port C, 22.8 cm, with an approach angle of 66.8°; and from auxiliary port D, 15.4 cm, with an approach angle of 12.5° (Fig. 8).

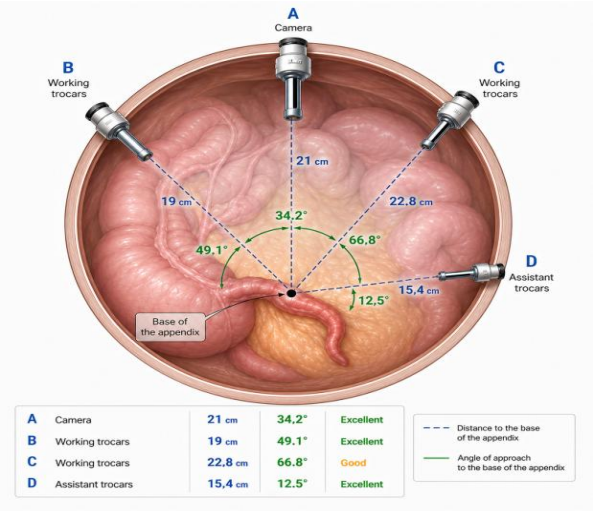


Figure 8. Schematic representation of trocar positions and calculated approach angles to the target region

Using the triangulation-based model and the “Laparoscopic appendectomy” software, we identified individualized trocar entry sites, insertion angles, and working distances for patients across BMI categories, including underweight, normal weight, overweight, class I obesity, and class II obesity (Table 7).

Table 7

Table 7. Proposed trocar-placement parameters for laparoscopic appendectomy across BMI categories

BMI	Point A	Point B	Point C	Point D
16– 18.5	Distance: 5.5 cm Insertion angle: 45.8 ± 1.0° Depth: 8.4 ± 0.2 cm Approach angle: 47.2 ± 1.0°	Distance: 8.5 cm Insertion angle: 49.1 ± 1.1° Depth: 9.9 ± 0.2 cm Approach angle: 52.9 ± 1.1°	Distance: 15.0 cm Insertion angle: 54.8 ± 1.2° Depth: 14.3 ± 0.3 cm Approach angle: 55.2 ± 1.2°	Distance: 3.0 cm Insertion angle: 18.0 ± 1.0° Depth: 7.0 ± 0.3 cm Approach angle: 17.7 ± 1.1°
18.5 – 24.9	Distance: 9.5 cm Insertion angle: 54.2 ± 1.3° Depth: 15.0 ± 0.4 cm Approach angle: 58.4 ± 1.5°	Distance: 12.5 cm Insertion angle: 58.7 ± 1.3° Depth: 16.3 ± 0.4 cm Approach angle: 60.2 ± 1.4°	Distance: 18.0 cm Insertion angle: 54.2 ± 1.5° Depth: 19.7 ± 0.5 cm Approach angle: 58.8 ± 1.5°	Distance: 4.5 cm Insertion angle: 29.4 ± 1.3° Depth: 8.6 ± 0.5 cm Approach angle: 31.6 ± 1.5°
25.0 – 29.9	Distance: 13.0 cm Insertion angle: 54.2 ± 1.3° Depth: 19.7 ± 0.5 cm Approach angle: 35.8 ± 1.3°	Distance: 14.0 cm Insertion angle: 45.9 ± 1.3° Depth: 18.3 ± 0.4 cm Approach angle: 49.1 ± 1.3°	Distance: 21.0 cm Insertion angle: 55.5 ± 1.4° Depth: 22.8 ± 0.5 cm Approach angle: 64.5 ± 1.4°	Distance: 6.5 cm Insertion angle: 12.5 ± 1.4° Depth: 10.4 ± 0.4 cm Approach angle: 15.5 ± 1.5°
30.0 – 34.9	Distance: 14.0 cm Insertion angle: 56.4 ± 1.5° Depth: 20.5 ± 0.5 cm Approach angle: 59.5 ± 1.6°	Distance: 13.0 cm Insertion angle: 52.3 ± 1.5° Depth: 18.7 ± 0.5 cm Approach angle: 56.3 ± 1.6°	Distance: 18.5 cm Insertion angle: 46.2 ± 1.7° Depth: 23.5 ± 0.6 cm Approach angle: 49.8 ± 1.7°	Distance: 6.5 cm Insertion angle: 21.4 ± 1.4° Depth: 11.0 ± 0.6 cm Approach angle: 24.6 ± 1.5°
35.0 – 39.9	Distance: 14.5 cm Insertion angle: 58.1 ± 1.6° Depth: 21.6 ± 0.6 cm Approach angle: 61.5 ± 1.7°	Distance: 12.5 cm Insertion angle: 64.3 ± 1.5° Depth: 19.0 ± 0.5 cm Approach angle: 65.9 ± 1.5°	Distance: 17.5 cm Insertion angle: 65.8 ± 1.6° Depth: 23.7 ± 0.65 cm Approach angle: 66.7 ± 1.6°	Distance: 6.5 cm Insertion angle: 22.5 ± 1.5° Depth: 13.0 ± 0.6 cm Approach angle: 25.2 ± 1.7°

An endoscopic protractor was used to measure the distance between the trocar and the target region, inter-port distances, and instrument insertion angles. The device provides intraoperative verification of the spatial parameters of laparoscopic access (Fig. 9).

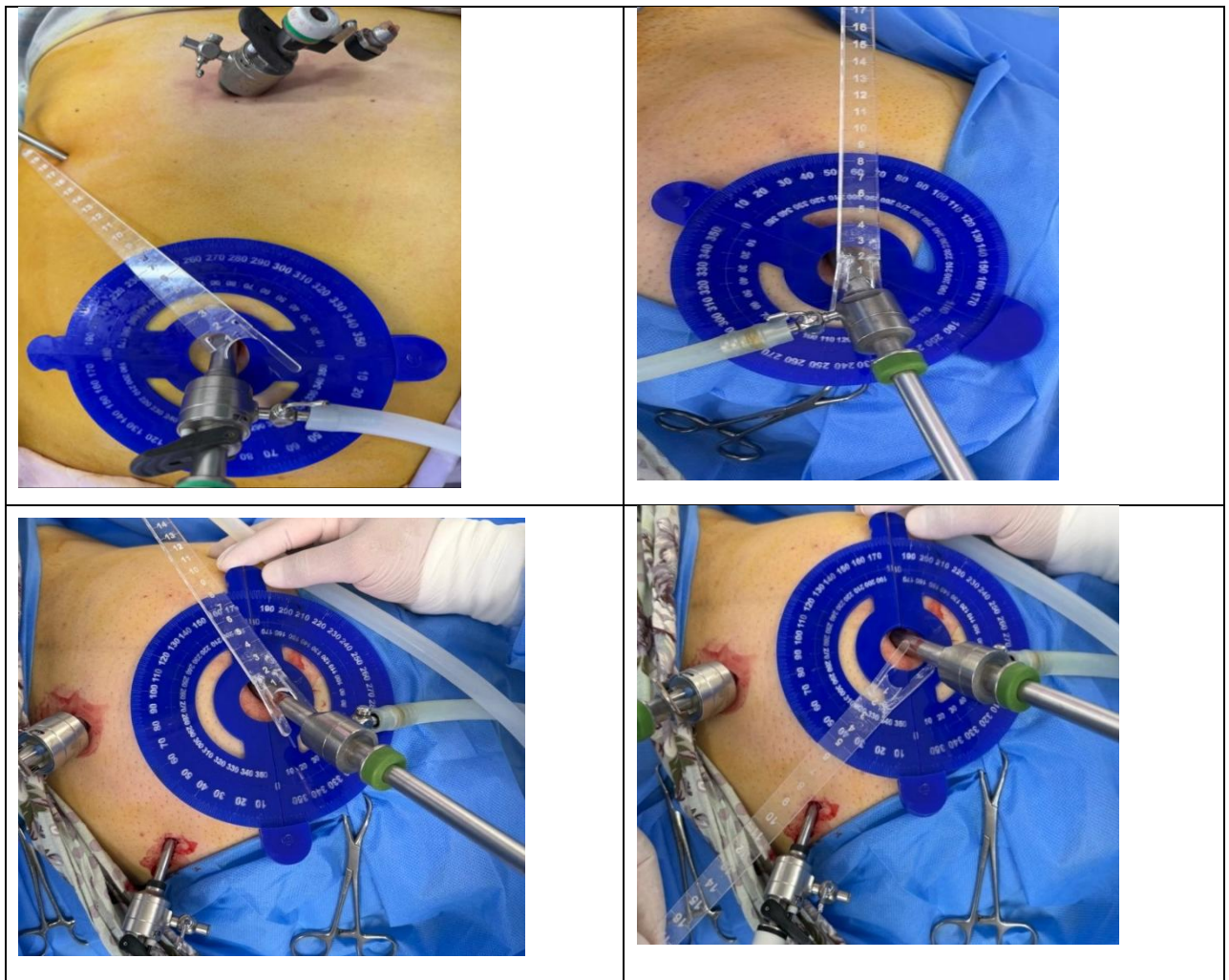


Fig. 9. Method of measuring angles and distances with an endoscopic protractor.

The device is placed on the abdominal wall, with the central aperture aligned to the planned access point. The protractor scale is used to measure the trocar insertion angle relative to the abdominal wall, while the sliding ruler measures distances between skin entry sites and assesses port symmetry. When necessary, the approach angle of the instrument toward the target organ can also be estimated.

In all 81 patients in the main group, laparoscopic appendectomy was attempted using individualized port planning with the “Laparoscopic appendectomy” software, and the appendiceal stump was treated with argon plasma coagulation.

According to commonly used laparoscopic appendectomy configurations, several patterns of working-port placement can be distinguished:

First configuration: two working trocars are placed in the right and left iliac regions. Although this layout appears symmetrical, it may be ergonomically unfavorable because one working instrument may remain insufficiently advanced into the abdominal cavity, increasing external handle excursion and reducing precision.

Second configuration: one trocar is placed in the left iliac region and the second is placed supraumbilically or in the right mesogastrium. This arrangement may create spatial competition between the operating surgeon and the camera assistant, limiting instrument movement and impairing visualization.

Third configuration: working trocars are placed in the suprapubic and right iliac regions. This layout may also be associated with suboptimal insertion depth and reduced ergonomic stability, particularly when the external instrument lever is excessively long.

Fourth configuration: working trocars are placed in the left iliac and suprapubic regions. This configuration is usually more favorable because it creates a more balanced triangular working field, provides a more ergonomic approach to the appendix, and reduces the likelihood of external hand collision and internal instrument crossing.

In selected difficult cases, the addition of a fourth trocar can improve retraction and visualization. A rational distribution of the camera and auxiliary instruments also reduces overlap between the surgeon and assistant and may improve procedural safety.

In the main group, laparoscopic appendectomy was performed using a SAGES-4-based triangulation strategy and individualized calculations from the “Laparoscopic appendectomy” software. The standard layout included a 10-mm periumbilical camera port, a main working port near McBurney’s point, and a suprapubic working port, with an auxiliary port added when required.

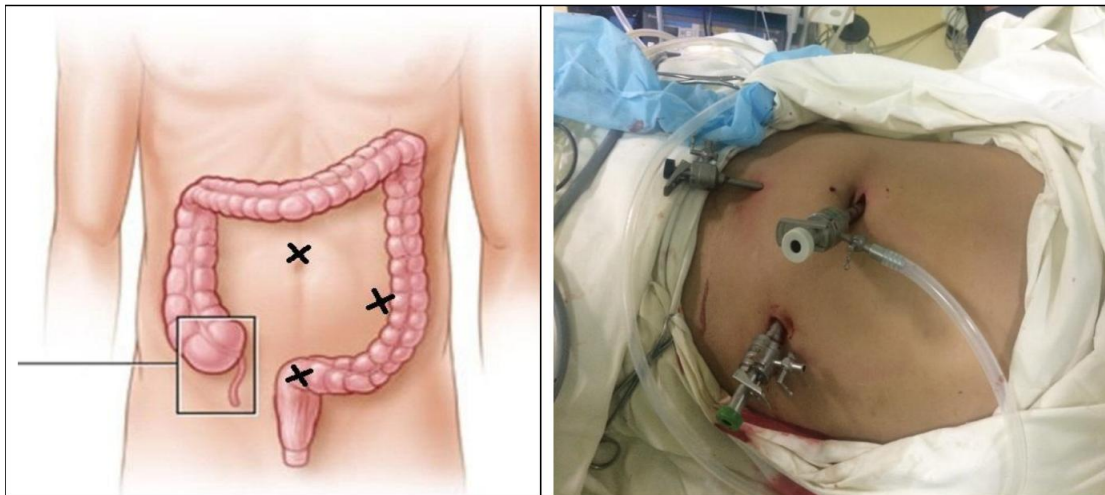


Figure 10. Sector-based trocar-access configuration: SAGES type 4.

Based on mathematical calculations and analysis of spatial trocar configurations, the most rational site for an additional fourth trocar was the right mesogastric region along the midclavicular line, approximately 2–3 cm above the umbilicus in patients with a BMI of 18.5–24.9 kg/m². This site provides effective retraction while minimizing instrument collision and avoiding major vascular structures of the anterior abdominal wall.

The spatial separation of the surgeon and assistant in this configuration reduces mutual interference, prevents crossing of instrument trajectories, and improves the ergonomics of retraction maneuvers involving the small bowel, greater omentum, and cecal region.

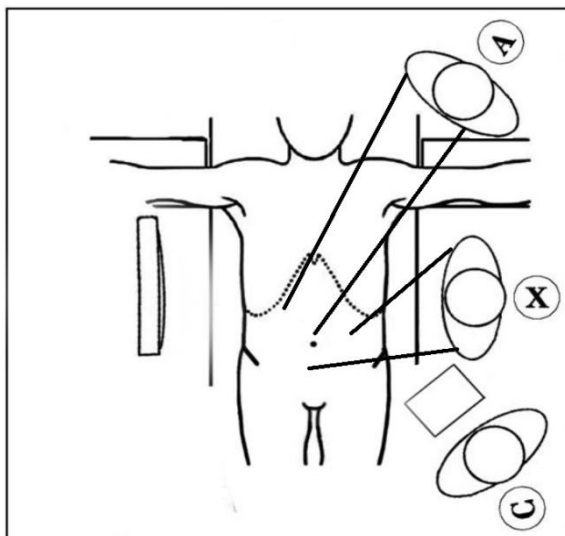


Figure 11. Operating-room layout during laparoscopic appendectomy. X, operating surgeon; A, camera assistant; C, scrub nurse.

A fourth trocar was required in 14 patients (17.3%) in the main group. No cases required repeated trocar repositioning because of insufficient reach or instrument conflict.

The appendiceal base was closed with conventional clips in 16 patients, Hem-o-lok clips in 38 patients, an endoscopic stapler in 11 patients, and an endoloop ligature using Vicryl 2-0 in 16 patients.

Conventional clips were used primarily in catarrhal appendicitis and in selected phlegmonous cases when the appendiceal diameter did not exceed 6-8 mm. Hem-o-lok clips were preferred in phlegmonous appendicitis when the appendiceal base measured approximately 10-12 mm and tissue integrity was preserved. Clip-based closure was avoided in the presence of base necrosis, severe edema, friable tissue, gangrenous inflammation, or marked inflammatory infiltration of the cecal dome because of the potential risk of clip slippage and stump insufficiency.

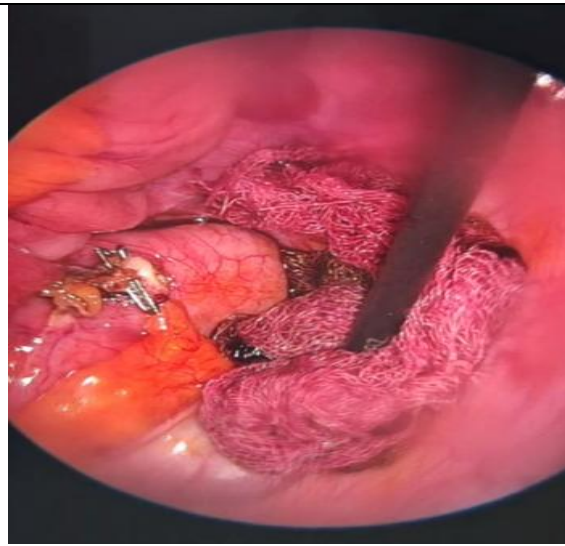


Figure 12. Application of a conventional clip to the appendiceal base

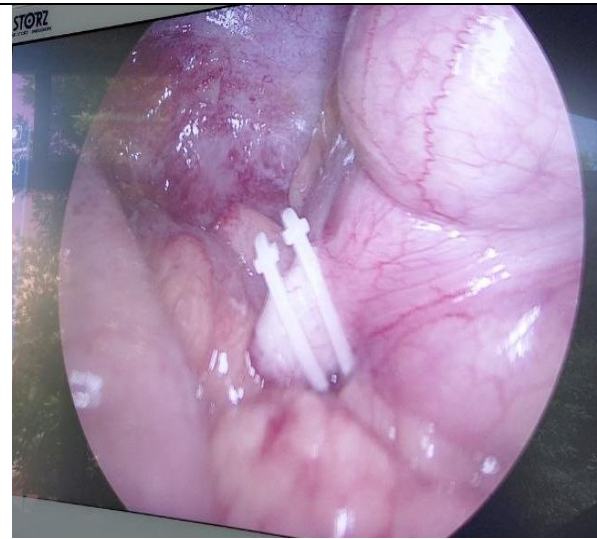


Figure 13. Application of a Hem-o-lok clip to the appendiceal base

Endoloop ligation remains a widely accepted option for appendiceal stump closure and may be used when the stump diameter is up to approximately 20 mm. In gangrenous appendicitis or markedly friable tissue, however, it should be applied cautiously because excessive tightening may cut through the inflamed appendiceal base.

Endoscopic stapling provides simultaneous transection and secure closure of the appendiceal base and is particularly useful when tissue quality is compromised. In the present study, stapling was preferred for gangrenous appendicitis, necrosis of the appendiceal base, pronounced periappendiceal infiltration, suspected perforation at the base, or an appendiceal diameter greater than 12 mm.



Figure 14. Endoloop ligation of the appendiceal base

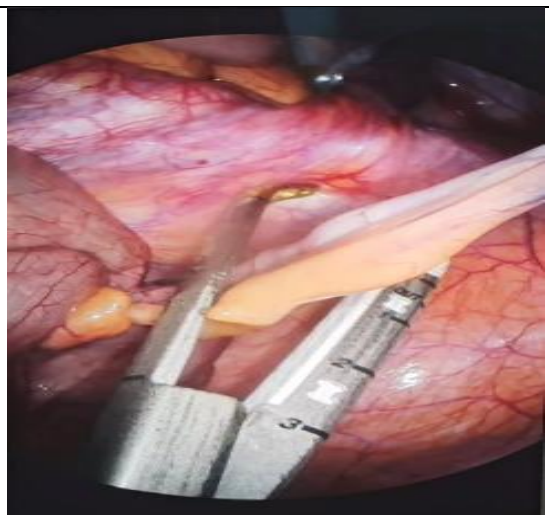


Figure 15. Application of an endoscopic stapler to the appendiceal base

In the main group, argon plasma coagulation (APC) was performed using the Electropulse SRCHPA-350 system (Tomsk, Russia), a monopolar high-frequency argon plasma coagulation device (Fig. 16).



Figure 16. Argon plasma coagulation system used in the study.

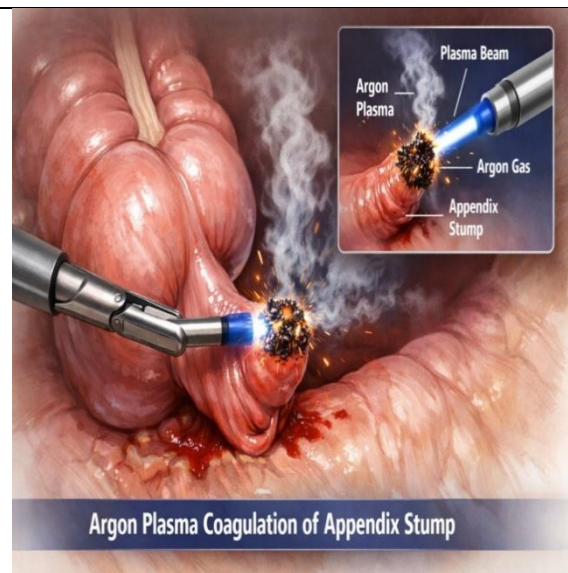


Figure 17. Argon plasma coagulation of the appendiceal stump during laparoscopic appendectomy.

The device provides several coagulation modes. The Fulgur mode is intended for deeper forced APC, whereas the Spray mode produces more superficial and uniform coagulation. In this study, Spray mode was applied through a 5-mm trocar at a non-contact distance of 3-5 mm, with power set at 20-30 W and argon flow at 0.8-1.2 L/min. Energy was delivered in short pulses of approximately 1 second while the plasma arc was moved circumferentially around the appendiceal stump, avoiding prolonged exposure at a single point. The stump was subsequently treated with 10% iodine solution.

Potential advantages of APC over conventional monopolar electrocoagulation include the following:

non-contact energy delivery, which reduces adherence of the instrument tip to inflamed tissue;

minimal traction on friable tissue, which may reduce the risk of mechanical disruption during coagulation;

reduced tissue carbonization and less need for repeated instrument cleaning;

more controlled superficial coagulation depth, provided that appropriate power, flow, and exposure settings are used;

more homogeneous surface coagulation through energy transfer by ionized argon;

short-pulse application, allowing the surgeon to titrate the thermal effect and avoid excessive exposure at a single point.

To evaluate the microbiological effect of stump treatment, we performed a pilot bacteriological comparison in two small patient subgroups.

In the first subgroup of 10 patients, cultures were obtained from the appendiceal stump after conventional monopolar electrocoagulation.

In the second subgroup of 10 patients, cultures were obtained after APC treatment of the appendiceal stump. The results were compared to assess residual microbial contamination and the potential local antiseptic effect of the two thermal methods.

After monopolar electrocoagulation, residual bacterial contamination persisted at 10^2 - 10^4 CFU/mL, with a mean value of 3.6 ± 0.26 log CFU/mL. After APC, no microbial colony growth was detected in the examined cultures.

Microbiological analysis showed a predominance of aerobic microorganisms, including *Staphylococcus aureus*, *Streptococcus* spp., *Escherichia coli*, and *Pseudomonas aeruginosa*. Anaerobic organisms, including *Prevotella melaninogenica* and *Bacteroides fragilis*, were detected less frequently.

The persistence of microbial contamination after monopolar electrocoagulation may be related to uneven thermal distribution and predominantly superficial coagulation. Areas of excessive carbonization may coexist with zones of insufficient thermal exposure, allowing microorganisms to persist in tissue microdefects or deeper layers of the appendiceal stump.

APC provides non-contact energy transfer through an ionized argon stream and may create a more uniform superficial thermal effect. This mechanism may contribute to better destruction of surface microbial biofilm and a lower likelihood of residual contamination on irregular stump surfaces. These findings should nevertheless be interpreted as preliminary because the microbiological subgroup was small and was not powered for definitive comparative conclusions.

In patients with peritonitis, pelvic drainage was performed selectively when intraoperative contamination was considered clinically significant. Drainage was not used in 52 patients, whereas drainage of the pelvis and left paracolic gutter was performed in 7 cases.

The mean operative time in the main group was 72.1 ± 6.8 min.

Postoperative hospital stay in the main group ranged from 2 to 7 days, with a mean duration of 3.2 ± 1.5 days.

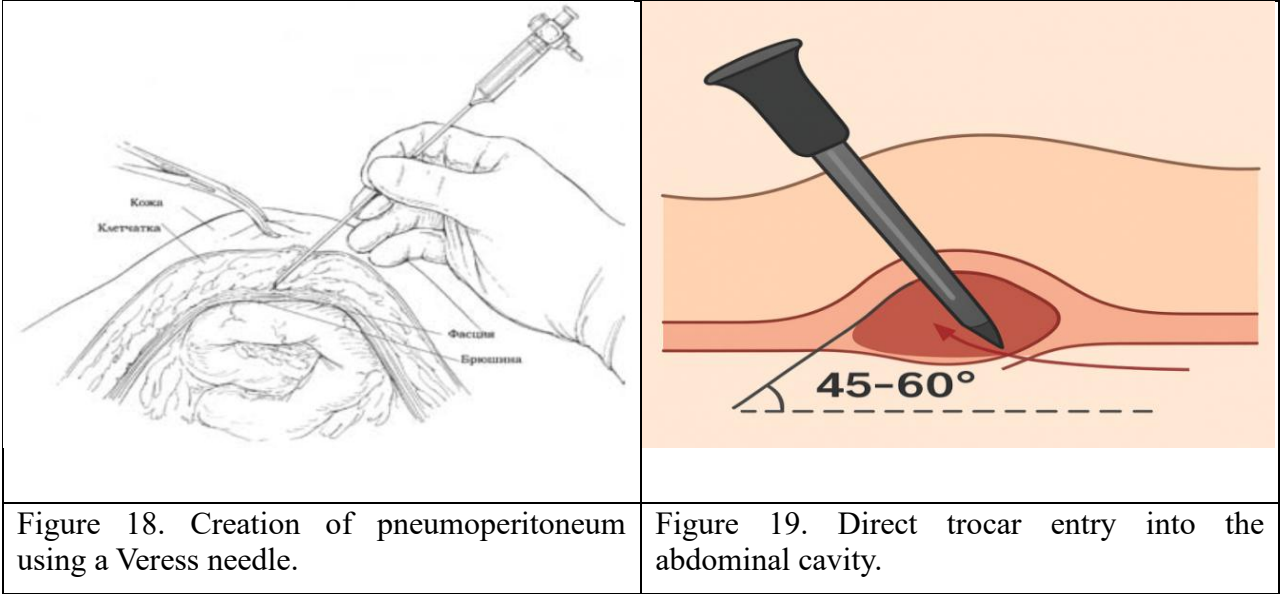
Conversion to open appendectomy was required in 2 patients (2.5%) in the main group. In one case, conversion was performed because of a gangrenous retrocecal appendix with dense inflammatory adhesions and inflammatory involvement of the cecal dome. In the second case, conversion was required because of a periappendiceal abscess combined with additional intra-abdominal abscesses and diffuse feculent-purulent peritonitis.

Postoperative complications occurred in 1 patient (1.2%) in the main group. This patient had undergone conversion for diffuse feculent-purulent peritonitis and subsequently developed

wound infiltration and suppuration at the median laparotomy incision. The complication was managed by local wound care, drainage, and systemic antibiotic therapy. During follow-up, an incisional hernia was diagnosed 4 months after surgery.

Technical requirements for trocar placement

Safe trocar placement requires consideration of abdominal wall thickness, patient habitus, target-organ depth, intra-abdominal adhesions, and the intended direction of instrument movement.



For initial access, the patient is placed in the supine position. After a small paraumbilical skin incision, the Veress needle may be introduced obliquely at approximately 45°-60° to the abdominal wall. Entry should be guided by standard safety checks and careful tactile perception of passage through the abdominal wall layers. Direct optical access or an open technique may be selected when clinically indicated, particularly in patients with previous abdominal surgery or suspected adhesions.

In patients with obesity or a thick abdominal wall, the effective intracorporeal working length of laparoscopic instruments decreases. The camera and working ports may therefore need to be positioned closer to the target region while preserving adequate triangulation and avoiding external handle crowding.

During laparoscopic appendectomy, the surgeon works within a triangular configuration formed by the camera and two working instruments. Perpendicular trocar insertion may limit the natural working trajectory and increase the risk of inadvertent injury to the bowel, mesentery, or vessels. Conversely, an excessively shallow insertion angle may increase the risk of preperitoneal dissection, trocar instability, and subcutaneous emphysema. An oblique insertion angle of approximately 45°-60° is generally preferable, whereas the broader ergonomic corridor is approximately 45°-75°.

Proper trocar placement should provide direct access to the target region, stable visualization, adequate instrument reach, and minimal external hand collision. It should also reduce the need for trocar repositioning, shorten technically difficult operative steps, and improve recognition of anatomical structures in inflamed tissues.

Ports should not be placed too close to rigid anatomical boundaries, such as the costal margin, xiphoid process, or pelvic bones, because these structures restrict instrument mobility. Working ports should usually be separated by at least 5 cm and should not be arranged parallel to one another. Instruments should converge toward the target with a sufficiently wide manipulation angle while avoiding excessive divergence, which reduces precision.

The number of trocars should be determined by the target organ, the degree of inflammation, the need for retraction, and the technical complexity of the case. Although standard laparoscopic appendectomy is usually feasible with three ports, an additional auxiliary port may be justified when retraction is inadequate or visualization is limited.

The video monitor should be positioned along the optical axis toward the operative field. Instruments should move toward the monitor rather than away from it. A manipulation angle close to 60°, combined with an appropriate elevation angle, provides favorable ergonomics for dissection, coagulation, and intracorporeal suturing when required.

DISCUSSION

Summary of principal findings

The principal finding of this retrospective-prospective cohort study is that individualized software-assisted trocar-placement planning was associated with a substantial improvement in the technical and early clinical outcomes of laparoscopic appendectomy for acute appendicitis. Compared with conventional trocar placement, the proposed strategy reduced conversion from 31.3% to 2.5%, eliminated repeated trocar repositioning, reduced postoperative complications from 16.5% to 1.2%, and shortened the mean postoperative hospital stay from 4.7 ± 1.3 to 3.2 ± 1.5 days. These improvements were observed despite comparable baseline distributions of age, sex, BMI category, inflammatory form of appendicitis, time from symptom onset to admission, and peritonitis severity. The results therefore suggest that the geometry of laparoscopic access is a clinically relevant and modifiable factor in technically difficult emergency laparoscopy.

The reduction in conversion should be interpreted cautiously because treatment allocation was not randomized and the groups were defined by treatment period. Nevertheless, the magnitude of the observed difference and the parallel improvement in access-related technical endpoints support the hypothesis that patient-specific port planning improved the operative working environment. The absence of repeated trocar repositioning in the main group is particularly important, because repositioning usually reflects inadequate initial access, insufficient instrument reach, poor triangulation, or internal and external instrument conflict.

Comparison with previous studies

Current emergency-surgery literature supports laparoscopic appendectomy as the preferred operative approach for most suitable patients with acute appendicitis, while recognizing that complicated inflammation, abscess formation, diffuse peritonitis, obesity, and atypical appendiceal position increase technical difficulty and postoperative risk [2-4, 9]. Most published studies have focused on the choice of laparoscopic versus open surgery, stump-closure methods, drainage strategies, infectious complications, length of stay, and antibiotic therapy. In contrast, trocar placement is often treated as a routine technical detail and is rarely analyzed as an independent determinant of operative feasibility.

The present study extends this field by evaluating trocar geometry as a measurable component of surgical quality. Standard port maps are useful in routine appendectomy, but they may be less reliable when pneumoperitoneum changes abdominal-wall geometry, when obesity increases the effective working distance, or when inflammation fixes the appendix in a retrocecal or retroperitoneal position. In such situations, a small difference in trocar position may determine whether the surgeon can achieve adequate traction-countertraction, safely control the mesoappendix, and close the appendiceal stump without excessive tissue tension.

Recent work in minimally invasive surgery, surgical ergonomics, image-guided procedures, and robotic surgery increasingly treats instrument trajectories, port spacing, working angles, and surgeon posture as geometric and kinematic problems rather than purely subjective choices. The proposed model applies this concept to conventional emergency laparoscopy. Its practical advantage is that it does not require expensive navigation or robotic platforms: anthropometric

data, estimated target depth, geometric calculations, and direct intraoperative angle verification are combined into a low-cost planning workflow.

Mechanistic interpretation

Several mechanisms may explain the association between individualized access planning and improved outcomes. First, optimization of working distance helps preserve the effective intracorporeal length of the instrument and reduces excessive external handle excursion. Second, maintaining an appropriate approach angle improves tissue traction and countertraction, reduces parietal-wall tension, and facilitates fine dissection in inflamed tissues. Third, adequate inter-port distance reduces internal instrument crossing and external hand collision. Fourth, matching port position to BMI and target-organ depth may be especially useful in patients with a thick abdominal wall, in whom standard trocar maps can leave the instrument too short or too tangential for safe mobilization of the appendix.

The mathematical model and software should not be interpreted as a replacement for surgical judgment. Rather, they provide a structured decision-support tool that transforms trocar placement from a subjective estimate into a reproducible and measurable step. The endoscopic protractor-goniometer adds intraoperative verification by allowing the surgeon to measure insertion angles and inter-port distances directly on the abdominal wall. This combination of preoperative or intraoperative calculation with real-time verification represents the main methodological contribution of the study.

Adjunctive APC should be considered a complementary component of the strategy rather than the sole explanation for improved outcomes. Secure stump closure remained dependent on appropriate mechanical closure with conventional clips, polymeric clips, endoloops, or stapling according to stump diameter and tissue quality. The pilot microbiological analysis suggested that APC may reduce residual bacterial contamination on the appendiceal stump, but the subgroup was small and not powered for definitive clinical conclusions. Larger studies should separate the effects of port planning, stump-closure method, and APC on infectious outcomes.

Clinical implications

The clinical value of the proposed approach is threefold. First, it provides a practical method for individualized port placement in patients whose anatomy, BMI, inflammatory pattern, or appendix position does not match standard trocar maps. Second, it may improve intraoperative decision-making by allowing the surgeon to adjust the planned port site before trocar insertion when the calculated working distance or approach angle is unfavorable. Third, it provides an objective educational framework for teaching triangulation, working depth, fulcrum mechanics, and instrument conflict to trainees.

The approach may also improve operative documentation and quality control. Recording calculated port positions, measured insertion angles, intraoperative access difficulties, and the need for port correction could facilitate audit of laparoscopic ergonomics and enable multicenter comparison of access strategies. From a health-system perspective, fewer conversions, fewer complications, and shorter hospitalization may reduce resource use, although formal cost-effectiveness analysis was not performed in the present study.

Strengths and limitations

The strengths of this study include a clinically relevant emergency-surgery cohort, comparison with conventional practice, objective assessment of access-related technical difficulty, integration of mathematical modeling with intraoperative measurement, and inclusion of early clinical outcomes. Another strength is the practical nature of the intervention: the software-assisted planning method and endoscopic protractor-goniometer may be implemented in centers where emergency laparoscopy is available but advanced navigation systems are not.

Several limitations must be acknowledged. First, this was a single-center non-randomized study, and group allocation was based on treatment period rather than randomization. Second, the control group was retrospective whereas the main group was prospective, creating potential temporal and selection bias. Third, the intervention combined software-assisted planning, protractor-based measurement, optimized trocar layout, and APC; therefore, the independent contribution of each component cannot be fully separated. Fourth, the microbiological subgroup was small. Fifth, long-term outcomes, validated ergonomic scores, surgeon workload, instrument-motion metrics, and cost-effectiveness were not assessed. These limitations mean that the results should be interpreted as hypothesis-generating and require external validation.

Future research

Future studies should evaluate this strategy in prospective multicenter cohorts using randomized or propensity-matched designs. Objective ergonomic endpoints such as surgeon posture, muscle activity, hand-collision frequency, instrument-motion analysis, task-completion time, and workload scores should be incorporated. Further development may integrate ultrasonographic or computed-tomographic target-depth estimation, augmented reality, or machine-learning-based prediction of optimal port sites. Separate evaluation of APC and stump-closure strategies is also needed to clarify their independent contribution to infectious outcomes.

CONCLUSIONS

1. Individualized software-assisted trocar-placement planning based on geometric modeling significantly improved the technical and early clinical outcomes of laparoscopic appendectomy. Compared with conventional trocar placement, the proposed strategy reduced conversion from 31.3% to 2.5%, eliminated repeated trocar repositioning (25.2% to 0%), decreased postoperative complications from 16.5% to 1.2%, and shortened postoperative hospital stay from 4.7 ± 1.3 to 3.2 ± 1.5 days.
2. Integration of patient anthropometric parameters, estimated target-organ depth, working distance, insertion angle, triangulation principles, and intraoperative verification with an endoscopic protractor-goniometer provides a reproducible framework for precision trocar placement. This approach may improve ergonomics, reduce instrument conflict, standardize intraoperative decision-making, and serve as a useful educational tool for teaching laparoscopic access planning.
3. The proposed strategy should be considered a promising patient-specific approach for technically difficult emergency laparoscopic appendectomy. However, because this was a single-center non-randomized study and the intervention combined software planning, angle verification, optimized trocar layout, and APC, larger prospective multicenter studies are required to validate the findings and determine the independent contribution of each component.

DECLARATIONS

Ethics approval and consent to participate

The study protocol was approved by the Local Ethics Committee of Tashkent State Medical University (Protocol No. 15, dated 16 April 2026). Written informed consent was obtained from patients included prospectively; anonymized retrospective data were analyzed in accordance with institutional ethical requirements.

Consent for publication

Not applicable. The manuscript does not include identifiable individual patient data.

Availability of data and materials

The datasets analyzed during the current study are available from the corresponding author on reasonable request, subject to institutional and ethical restrictions.

Competing interests

The authors declare that they have no competing interests.

Funding

No external funding was received for this study.

Authors' contributions

Kh.I.E. contributed to study conception and design, data collection, analysis, software-assisted modeling, drafting of the manuscript, and revision of the final version. M.Sh.K. supervised the study, contributed to surgical methodology, interpretation of results, and critical revision of the manuscript. Both authors read and approved the final manuscript. K.K.S. participated in patient management, data collection, data verification, manuscript editing, and approved the final version of the manuscript. All authors read and approved the final manuscript.

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