

Surgical smoke management for minimally invasive (micro)endoscopy: an experimental study

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Abstract

Background The aim of this study was to investigate the use of surgical smoke-producing procedures such as laser ablation or electrosurgery in minimally invasive microendoscopic procedures. This study proposes a technical solution to efficiently remove surgical smoke from very small endoscopic cavities using microports as small as 20 G (0.9 mm) in diameter.

Methods The experimental laboratory study used small, rigid, transparent plastic cavity models connected with tubes and pressure sensors to establish an endoscopic in vitro laboratory model. A Kalium-Titanyl-Phosphate (KTP) laser with a 0.5-mm fiber optic probe was used to produce smoke from bovine scleral tissue in the cavity. Endoscopic gas insufflation into the model was generated by pressurized air and a microvalve. A laboratory vacuum pump provided smoke and gas suction via a microvalve. A self-built control and steering system was utilized to

control intracavitary pressure during experimental insufflation and suction.

Results Problems related to smoke-generating processes, such as laser vaporization or electrocautery, in small closed cavities were first analyzed. A theoretical and mechatronic laboratory model was established and tested. Intracavitary pressure and gas flow were measured first without and then with smoke generation. A new construction design for the suction tube was proposed due to rapid obstruction by smoke particles.

Conclusions Surgical smoke evacuation from endoscopic cavities that are as small as 2 cm in diameter via minimally invasive ports as small as 20 G (0.9 mm) in diameter may be safe and efficient if sufficient gas exchange is provided during smoke generation by laser or electrosurgical instruments. However, maintaining a low and constant pressure in the cavity during gas exchange and adopting a special construction design for the suction tube are essential to provide an excellent view during the surgical maneuver and to minimize potential toxic side effects of the smoke.

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Minimally invasive surgery is increasingly becoming the preferred treatment option for numerous surgical indications. Endoscopic procedures have been developed and refined by a variety of technical advancements to minimize operation time, side effects, and the risk of surgical and postoperative complications [1–5]. However, electrosurgery and laser tissue ablation with these endoscopic techniques are limited by the development and amount of surgical smoke, which can dramatically reduce visibility

[6–10]. Smaller endoscopic cavities and greater quantities of smoke worsen the conditions even further.

Surgical smoke has been shown to contain toxic and mutagenic chemicals [11–15]. The hazards of surgical smoke and the risks associated with exposure to it for both patients and perioperative personnel have been reviewed [7, 16, 17]. In addition, if the endoscopic cavity is closed and laser ablation is regarded as a thermal combustion process, the production of combustion gases such as CO₂, CO, or NO_x could cause an increase in pressure and/or volume. Hence, microendoscopic laser tissue ablation or cauterization may result in the trapping of a significant amount of smoke in a small cavity of the human body, reducing visibility for the surgeon and causing toxic effects for the patient. Thus, the purposes of the present study were (1) to investigate the feasibility of smoke-producing surgical procedures, such as laser ablation or electrocautery, in microendoscopic minimally invasive surgery and (2) to develop technical solutions for highly effective smoke evacuation with intracavitary pressure control.

As our experimental research is intended for use in any endoscopic procedure in any field of the human body for any type of laser or electrosurgery, we performed standardized *in vitro* investigations with small, ball-like, transparent, rigid standard cavities ranging from 2 to 5 cm in internal diameter (cavity volumes of 4.2–65.4 cm³). An additional goal was to miniaturize the diameters of the insufflation and smoke evacuation tubes so as to minimize the wound sizes for the endoscopic ports in the human body. For better visibility and to avoid the use of an endoscope for this experimental study, we chose to use a transparent plastic cavity. Another aim was to control the elimination of even extensive smoke (e.g., that arising from laser vaporization of tissue). Our results are presented in consecutive steps to show the problems encountered in the development of the new evacuation system and to present our proposed solutions.

Materials and methods

Part 1. Experiments without smoke evacuation for problem analysis

The following items were used to construct the experiment:

Cavity model

Rigid transparent polypropylene plastic balls with a diameter of 2 cm (volume = 4.2 cm³), 3 cm (volume = 14.1 cm³), 4 cm (volume = 33.5 cm³), and 5 cm (volume = 65.4 cm³) and consisting of two cups stuck together with conventional contact glue (Patex, Henkel

GmbH) were used as endoscopic cavity models (Kaspar Harnisch GmbH, Graz, Austria).

Smoke generation

We used an Aura with Star Pulse KTP Laser (green 532 nm) with a 0.5-mm-diameter fiber optic probe (NWL Laserscope, CA, USA).

Organic tissue for surgical smoke generation

Bovine sclera provided by the teaching unit of the Department of Ophthalmology (Medical University of Graz, Austria) was used to fill the cavity models.

The laser probe was introduced through a small hole for smoke production. In order to evaporate tissue, we chose laser parameters of 7 W of continuous wave (cw) and a duration of 2 s.

Part 2. Experimental model for an endoscopic smoke evacuation system

In addition to Part 1, the following mechanical and electronic parts were used for the experimental model presented in the Results section.

Mechanical parts

The miniature, amplified, low-pressure sensor HCLA0075GU (Sensor Technics GmbH, Germany) was connected by a thin tube (23G medical needle) to the plastic cavity. The sensor delivered pressure data continuously to the control unit.

The Analyt GFM 17 mass flow sensor device (0–5 standard liters/min, Analyt MTC Messtechnik GmbH, Germany) was connected to the inlet valve to monitor mass flow through the cavity.

A KPI-TP-10-13-50 mini-proportional inlet valve (Kelly Pneumatics, Costa Mesa, CA, USA) was used to control insufflation gas.

A KPI-TP-10-40-50 mini-proportional valve (Kelly Pneumatics) was used as a vacuum outlet valve.

Plastic tubes 4 mm in diameter (Conrad Electronic GmbH, Austria) were connected by tube fittings for 4-mm plastic tubes (Conrad Electronic GmbH, Austria).

Medical needles of various diameters—16 G (gauge) (1.3 mm), 18 G (1.0 mm), 20 G (0.9 mm), and 23 G (0.6 mm)—connected to the 4-mm-diameter plastic tubes were used as inlet and outlet tubes (B. Braun Melsungen AG, Germany).

Pressurized gas was provided by the hospital's central medical air system (maximum pressure = 8 bar, Medical University of Graz, Austria).

A laboratory vacuum pump was used as a vacuum source (maximum = -0.8 bar, maximum flow = 20 l/min, Medical University of Graz, Austria).

Mechatronic model—control unit

For data acquisition and output, we used a NI cDAQ-9172 hardware chassis, including data acquisition modules NI9205 and NI 9263 (National Instruments GmbH, Salzburg, Austria). The hardware chassis was connected to a Dell D420 laptop computer.

The software for data acquisition and the software controller were programmed in Labview 7.1 (National Instruments GmbH, Salzburg, Austria) [18].

Part 3. Testing gas exchange with pressure and flow monitoring without smoke production

The system in Part 2 was tested. Data were recorded by Labview 7.1 and analyzed with Matlab vR12.

Part 4. Testing gas exchange with smoke production by a KTP laser

In order to visualize precipitations in the tube, we used the materials from the preceding experiments (Parts 1–3) in addition to silicone rubber tubes that have an inner diameter of 1 mm and an outer diameter of 3 mm (ESSKA Maschinenvertriebs GmbH, Hamburg, Germany).

Part 5. Development of a new suction unit

In addition to the materials from the previous sections, we used the following items to construct the suction unit:

The 20-G (0.90 mm) high-viscosity injectors, which were originally intended for silicon oil injections during eye operations (BD, Waltham, MA, USA), were used as inlet and outlet tubes.

Disposable inlet and outlet filters (Balston, Grade BQ, Parker, Vienna, Austria) were inserted into the gas stream to purify the inlet and outlet gases, the inlet filter before the inlet valve, and the outlet filter before the outlet valve.

Medical needles with a diameter of 30 G (0.3 mm) were utilized to inject balanced saline solution (BSS) in front of the suction tube in order to prevent blockages in the tube (B. Braun Melsungen AG, Germany).

The construction design described above can be seen in Fig. 6. The standard hospital motor infusion system for liquid injection (B. Braun Melsungen AG) used a flow rate of 70 ml/min to transport BSS from a syringe in the motor infusion system to the 30-G injection tube.

Results

Part 1. Experiments without smoke evacuation for problem analysis

The first part of our study consisted of problem analyses and visualization of the smoke-producing endoscopic procedures. For this purpose, transparent plastic endoscopic cavity models of various sizes (diameters of 2–5 cm) were filled with bovine scleral tissue. We used no endoscopic ports with insufflation or smoke evacuation tubes in order to simply observe what happens when surgical smoke emerges. The 0.5-mm-diameter fiber optic laser probe was inserted into the plastic cavity through a small hole to deliver the smoke-producing laser energy.

Laser vaporization of the tissue produced a significant amount of smoke, which immediately filled the plastic cavities and completely obstructed the surgeon's view (the duration of smoke production was 2 s). The smaller the cavity diameter, the faster this filling process occurred. After cessation of the experimental smoke production, the cavity slowly cleared, beginning at the top of the cavity. This clearing process continued steadily until the smoke had completely disappeared. We observed clearing times ranging from 12 to 43 s, depending on the diameter of the cavity. Larger cavities had shorter clearing times. Interestingly, the smoke precipitated as a blackish-brown semiliquid film on the inner wall of the plastic cavities during this clearing process. The smaller the cavity model, the more intense were the deposits that were observed.

Figure 1 shows a 2-cm-diameter plastic model before, during, and after laser application. Video 1 (first part) shows the sudden emergence of surgical smoke as well as the slow deposition process in the experimental endoscopic cavity.

Our first experiments elucidated the two problems of endoscopic surgical smoke production. First, the smoke severely obscured the surgeon's view. Second and more importantly, the smoke, which is assumed to be toxic and mutagenic, deposited on the walls of the endoscopic cavities. All of these hazardous substances at this location could easily be absorbed by in vivo endoscopic cavity tissue.

Part 2. Theoretical and experimental models for an endoscopic smoke evacuation system

Our first experiment demonstrated clearly that highly efficient smoke evacuation is essential while using surgical smoke-producing procedures such as laser or electrocautery in small endoscopic cavities. We also observed that smaller cavities would be even more difficult to manage than larger ones with respect to both the density of smoke

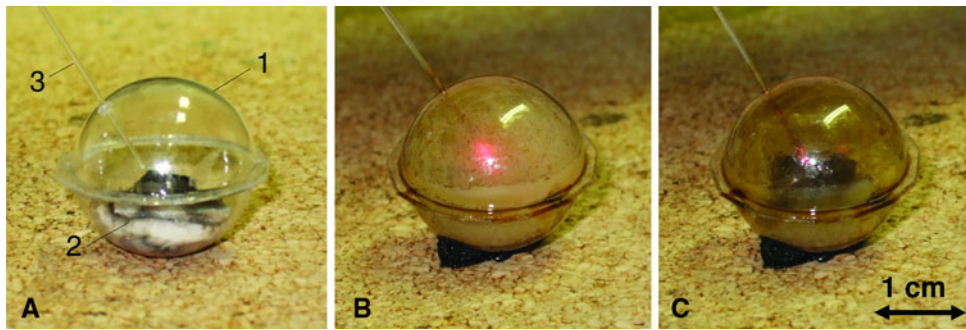


Fig. 1 Transparent plastic cavity model (2 cm in diameter) **A** before, **B** during, and **C** after smoke generation by the KTP laser. **A** A transparent plastic model (1) was filled with bovine scleral tissue (2) by sticking the two halves of the cavity model together with contact glue. A fiberoptic laser probe (3) was introduced through a small hole into the plastic cavity. **B** Laser energy (7 W, 3 s) was applied via the laser fiber to produce surgical smoke. Immediately after the beginning

of smoke production, the transparent ball was rapidly filled with dense smoke that completely obstructed the operator's view. **C** After the experimental smoke generation had stopped, the cavity slowly began to clear as the smoke precipitated on the inner walls of the cavity model. The picture shows the plastic cavity 2 min after the end of the smoke generation

and the deposits. Thus, our next step was to develop an experimental smoke evacuation system to avoid the previously mentioned two problems. However, the immense amount of smoke in the small cavity shown in our first experiments would require high suction performances. Because of the small volume of the cavity, this high suction performance would lead to a high gas exchange rate in the cavity and consequently to the danger of eventual intracavitary pressure fluctuations. Thus, we concluded that a suction device must not only demonstrate high suction performance but also provide intracavitary pressure control.

First we elaborated on a theoretical model for an experimental smoke evacuation device (Fig. 2A). An inlet tube for gas insufflation, an outlet tube for smoke evacuation, and a thin tube for pressure measurement were introduced into the experimental cavity. The inlet tube was connected to pressurized gas and the outlet tube was connected to a vacuum source. To regulate the insufflation and evacuation gas flow, the inlet and outlet tubes were furnished with microvalves controlled by a controller unit. The controller unit was designed as a software proportional integral (PI) algorithm. The purpose of the control system was to regulate the inflow and outflow of the gas in order to establish intracavitary pressure within narrow limits. The intracavitary pressure was measured continuously by a pressure gauge that was connected by a thin tube to the cavity. In addition, inlet and outlet filters were added.

The theoretical model was then reproduced as a laboratory experimental model (Fig. 2B). As smaller cavities offer more experimental difficulties than do larger ones, we decided to focus our experiments on the smallest cavity volume (2 cm diameter). As a further challenge, we used extremely small inlet and outlet tubes (20 G diameter). Two 20-G steel needles connected to silicon tubes were introduced into the plastic ball cavity: one provided fresh

gas/air and the other removed the smoke by suction. Pressurized gas was delivered by the hospital's central medical air system. A laboratory vacuum pump provided the vacuum. A miniature pressure sensor measured the intracavitary pressure gauge continuously. The inlet and outlet gas flows were controlled by a central steering unit (comprising data acquisition hardware, a laptop, and software controller) connected to the pressure sensors as well as to the inlet valve. Other materials used in this experimental setup are described in the Methods section and appear in Fig. 2B.

Part 3. Testing gas exchange with pressure and flow monitoring without smoke production

The experimental system was first tested without smoke production to determine its ability to provide efficient gas exchange as well as pressure control. The system managed an intracavitary gas flow of a maximum of 2 l/min. This means that the total intracavitary gas was exchanged eight times per second. During this continuous gas exchange, the control unit kept the intracavitary pressure at a constant low positive pressure level (5–30 mmHg) by means of the inlet valve. The purpose of the test shown in Fig. 1 was to assess (1) whether the pressure remained at a constant level during continuous gas exchange and (2) how quickly a desired new intracavitary pressure could be achieved. A diagram of the pressure-testing procedure appears in Fig. 3A and B. Randomly preset pressure levels between 5 and 30 mmHg were reached within 0.2 s and kept constant until the next change was induced (Fig. 3A). Figure 3B displays the mass flow in standard liters per minute (sl/min) during the testing procedure. In addition, disturbances (e.g., obstruction of a tube) were simulated successfully (data not shown).

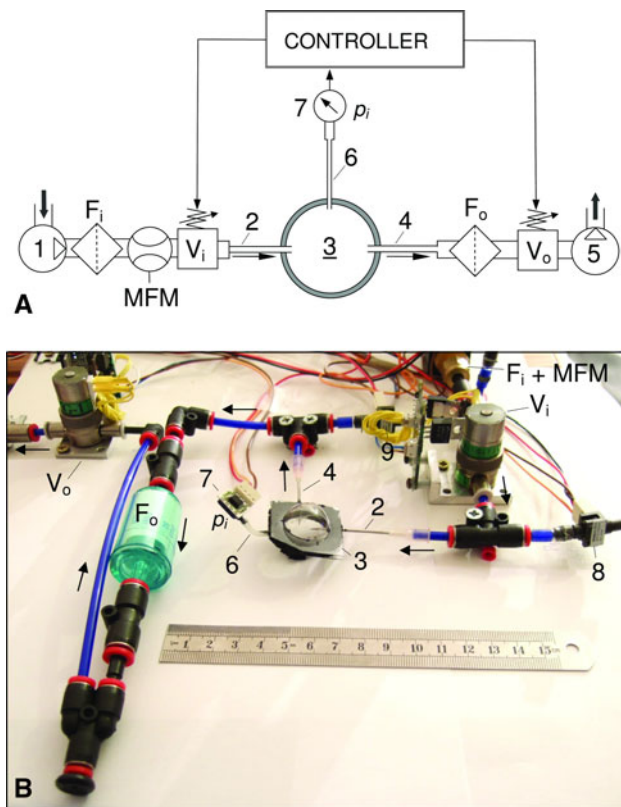


Fig. 2 **A** Theoretical model. **B** Experimental setup. Pressurized gas produced by a compressor (1) passes through an inlet filter (F_i), a mass flow meter (MFM), and the inlet valve (V_i). Afterward, the gas flows through an inlet tube (2) into the cavity model (3). Then, the gas is sucked by a sucking tube (4) introduced into the cavity, passes through the outlet filter (F_o), and exits through the outlet valve (V_o). The vacuum for sucking is produced by a vacuum pump (5). The pressure (p_i) in the cavity model (3) is measured via a thin pressure-transmitting tube (6) by a pressure sensor (7). The pressure data are delivered to a controller. The intracavitary pressure (p_i) should be kept constant during gas exchange. In order to achieve the desired gas flow rate through the cavity, the controller unit continuously adjusts the inlet valve (V_i) as well as the outlet valve (V_o) depending on the intracavitary pressure (p_i). The arrows indicate the flow direction. Additional pressure sensors (8) and (9) were used in the experimental setup for monitoring

Part 4. Testing gas exchange with smoke production by a KTP laser

Our next step was to test the system with experimental smoke production. Bovine sclera was placed into the transparent plastic ball as described in the Methods section. The gas exchange system, tested previously, was preset to an intracavitary pressure of 20 mmHg and the laser probe was inserted into the experimental cavity. Laser energy was applied in a noncontact mode to the scleral tissue in order to produce intense smoke. As smoke emerged, it was immediately drawn away by the evacuation tube. Unfortunately, the system worked very well only for a few

seconds. Within a few seconds the smoke had completely obstructed the outlet tube.

The intracavitary pressure and mass flow were monitored during the experiment (Fig. 4). As shown on the pressure graph (Fig. 4A), the laser induced pressure fluctuations of roughly 6 mmHg. Three laser pulses of about 2 s each were used. During the first smoke-generation procedure, no additional pressure peaks were observed. However, the mass flow declined from 1.2 to 1.0 sl/m. The second and third smoke pulses induced sudden pressure spikes that rose as high as 93 mmHg and as low as zero mmHg. Furthermore, the mass flow dropped continuously to a level of 0.2 sl/min within 20 s of smoke evacuation. After the experiment was concluded, we investigated the reason for this unexpected rapid decline in evacuation volume.

We analyzed the outlet tube and found a black-brown sticky mass obstructing the tube. To permit better visualization we repeated the experiment with a transparent silicone rubber tube that had an inner diameter of 1 mm (Fig. 5). These obstructing substances found in the suction tubes are known as soot. Soot is normally found in a chimney or exhaust pipe after incomplete or imperfect combustion of a hydrocarbon [19]. However, we were unable to improve the process of “tissue combustion” and thus had to search for an alternative solution to maintain the outlet tube in an open state.

Part 5. Development of a new suction unit

The following special construction arrangement (Fig. 6) kept even very thin tubes (up to 20 G) open successfully during the suctioning of the laser smoke.

In this arrangement small amounts of liquid are continuously injected in front of the beginning of the suction tube (Fig. 6A). A thin steel tube (30-G needle) that is introduced into the suction tube dispenses small amounts of liquid (e.g., roughly 70 ml/min of BSS provided by an infusion motor pump, Fig. 6B). The liquid binds the tiny smoke particles (Fig. 6A). The gas-fluid mixture is then sucked through the tube into a coalescing filter (not shown in the figure) where the liquid and gas can be separated.

The new suction device was successfully tested with smoke generation and pressure control during intracavitary gas exchange. Figure 7 shows the intracavitary pressure and gas flow during operation of the machine. The system remained stable, although small pressure peaks (± 5 mmHg) and fluctuations occurred during the laser treatment. All smoke was drawn away immediately. The intracavitary visibility remained excellent throughout the experiment. Furthermore, there was much less precipitation of smoke on the walls of the cavity than during the experiment without evacuation (Fig. 1).

Fig. 3 **A** Intracavitary pressure (p_i) in mmHg and **B** mass flow (f_i) in standard liters per minute (sl/min) during gas exchange in the experimental setup from Fig. 2 without smoke generation. The intracavitary pressure was randomly set to different levels (20, 10, 30, 10, and 5 mmHg) to test the reactivity of the system. The control system adapts the mass flow **B** to maintain the different pressure levels as shown in **A**. The desired intracavitary pressure can be maintained within narrow limits. Gas exchange at flow rates of roughly 1.2 sl/min worked steadily during the whole experiment

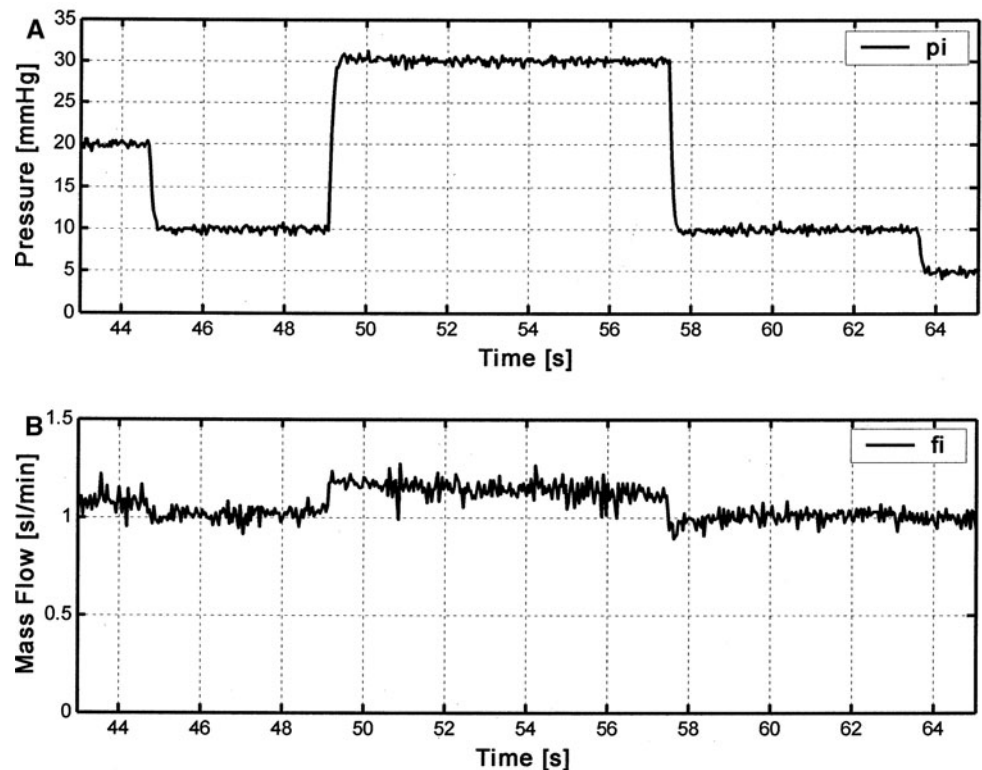
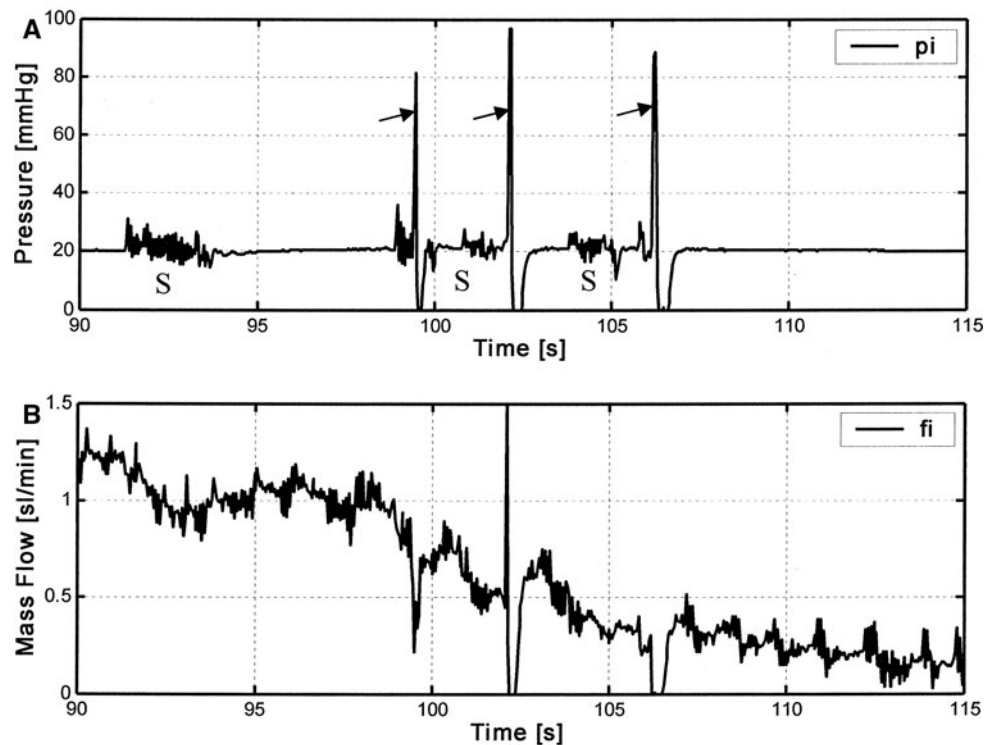


Fig. 4 **A** Intracavitary pressure (p_i) in mmHg and **B** mass flow (F_i) in standard liters per minute (sl/min) during intracavitary gas exchange in the experimental setup with pulsatile (2–3 s) laser smoke generation (S). **A** The intracavitary pressure was manually set to a constant level of 20 mmHg with a mass flow of 1.3 sl/min. The laser smoke generation (recognizable in the pressure chart by the small fluctuating pressure peaks) produced from the second smoke pulse onward caused high-pressure peaks reaching up to 95 mmHg and down to 0 mmHg (arrows). **B** The volume flow decreased constantly during the experiment and reached almost zero within 25 s after the beginning of smoke generation



Finally, we provide a video of the intracavitary smoke evacuation experiments using 20-G tubes of 0.9 mm in diameter (Video 1). In the first section smoke generation without any suction or gas exchange is shown to elucidate

the problem. Smoke is trapped in the small endoscopic cavity, which fills with smoke within a split second. In the second part, the final version of the experimental smoke evacuation system with the sucking device is demonstrated.

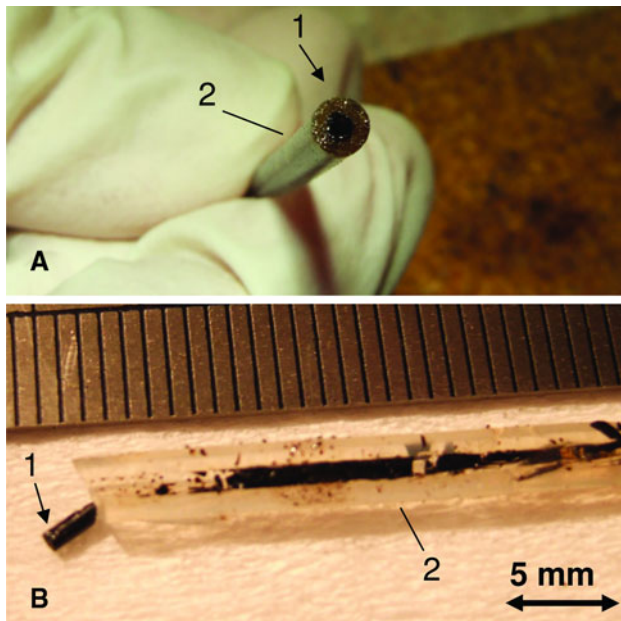


Fig. 5 An experimental sucking tube with an inner diameter of 1.0 mm was completely choked after 25 s of sucking surgical laser smoke. A transparent silicone rubber tube was used instead of the steel needles used in the preceding experiments to permit better visualization of the problem. **A** Black-brown sticky matter (soot) (1) obstructing the experimental sucking tube (2). **B** The sucking tube (1) was cut longitudinally after the sucking experiment to permit visualization of the soot (2)

The cavity model is connected to the insufflation tube on the left side and the sucking device (see Fig. 6) on the right side. The pressure in the cavity is continuously measured by a pressure sensor via thin steel tubes (medical needles) on the back of the cavity. The video shows that the cavity can be kept clear, even though the laser constantly produces extensive amounts of smoke. Smoke precipitation on the cavity walls was largely inhibited. The pressure and volume flow values of this experiment can be seen in Fig. 7.

Discussion

One of the major problems in using laser or electrosurgery during endoscopy is the presence of smoke or plume produced by the ablation of body tissues. In contrast to open surgery, smoke produced during laparoscopic and other endoscopic procedures is trapped in a closed gaseous space. As a result, potentially toxic chemicals produced inside the cavities are likely to be absorbed into the blood circulation and lead to systemic side effects [20, 21]. Furthermore, the smoke obscures the surgeon's vision.

During recent years, surgical techniques have been refined by a variety of technical advancements [3, 7, 10].

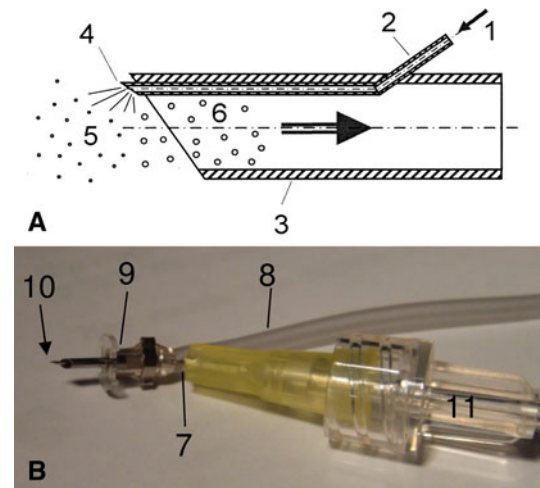


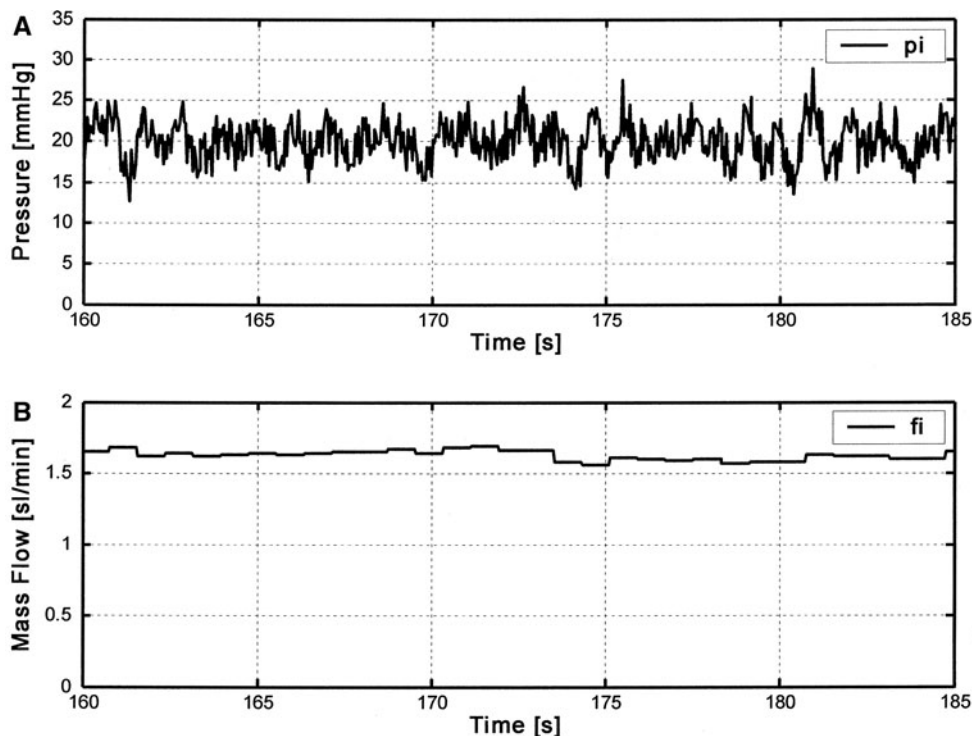
Fig. 6 Newly developed sucking device: **A** Schematic drawing. Sucking aid liquid (1) is pumped into a small feeding tube (2), which penetrates the wall of the sucking tube (3) to its front face. There, the sucking aid liquid is continuously injected (4). The sucking aid liquid absorbs and incorporates the smoke particles (5). The smoke and sucking aid fluid (6) are transported through the sucking tube (3) without allowing any undesired deposition on the inner surface of the sucking tube. **B** Experimental setup. A commercial 30-G medical injection needle (7) is used as a feeding tube. It penetrates the silicone hose (8) of the sucking tube and is inserted into the tube's steel portion (9). The tip of the 30-G needle (10) is visible at the front of the sucking tube. The feeding tube (30-G needle) is connected with a silicone hose to a commercial motor syringe infusion pump feeding saline solution (BSS) as a sucking aid liquid

However, to the best of our knowledge, the problem of surgical plumes in small endoscopic cavities has never been resolved satisfactorily. The dangers of intracavitary surgical smoke to both patients and operating room personnel have been discussed at length in the literature [7, 11, 13–16, 20, 21]. High temperature pyrolysis, as occurs during laser tissue ablation or electrosurgery, is known to produce cellular debris, breathable aerosols, and complex organic chemicals, including carcinogenic substances [7]. Various chemicals, including aldehydes, benzene, toluene, acrolein, hydrocyanic gases, and CO, have been identified in the plume [6, 12–15]. Consequently, laser and electrocautery smoke caused by the pyrolysis of tissue has been shown to be cytotoxic, genotoxic, mutagenic, and clastogenic [6, 11, 22–25].

To minimize any toxic side effects, Ott et al. [20, 21] and Barrett and Garber [7] recommend aggressive continuous or intermittent ventilation during laparoscopic operations that produce smoke in order to reduce intracavitary levels of CO and other toxins. Our experimental approach using continuous, high-volume ventilation should serve as a step forward in managing the noxious characteristics of surgical smoke. Future endoscopic smoke evacuation systems based on our experiments would permit laser and other smoke-producing operations to be better performed

Fig. 7 Intracavitary pressure (p_i) in mmHg (a) and mass flow (F_i) in standard liters per minute (sl/min) (b) during intracavitary gas exchange in the experimental setup with continuous laser smoke generation and the new sucking device as shown in Fig. 6.

A The intracavitary pressure was manually set to a constant level of 20 mmHg with a mass flow of 1.6 sl/min. The laser smoke generation permanently produced small pressure peaks (± 5 mmHg). **B** The mass flow was kept constant by preventing the sucking tube from becoming choked with surgical smoke



in existing and new minimally invasive endoscopic procedures.

Our new experimental device offers several advantages over conventional smoke evacuation techniques. First, the new technique allows us to minimize the patient's exposure to smoke by providing a maximum level of smoke evacuation. Due to the specially designed controlling and steering units, the system automatically provides high-volume intracavitary gas exchange for optimum smoke evacuation (intracavitary gas is exchanged up to eight times per second), while keeping the pressure in a constant range.

To prevent possible CO₂-associated complications (e.g., gas embolism, subcutaneous emphysemas, hypercarbia, and acidosis) and other known cardiovascular complications when performing endoscopic procedures, it is recommended that the lowest possible pressure level in each particular case be used [20, 21, 26, 27]. Our system can maintain a very low intracavitary pressure despite the high-volume gas exchange rate.

In our experiments we used air because it was easily available. However, any other gas would be suitable for the proposed system. Hensman et al. [6] showed that the type of atmosphere in which the smoke is produced (e.g., air vs. helium or CO₂) does not affect the nature of the toxic chemicals produced. The advantages and disadvantages of using different gases (e.g., CO₂, helium, argon, nitrous oxide, and air) are well known [26]. CO₂, the commonly used gas, is highly soluble and therefore rapidly absorbed. Although there is a very low incidence of gas embolism

with CO₂, it irritates the peritoneum when used in laparoscopy [26]. Hensman et al. [6] assumed that the vasodilatory effect of CO₂ on the serosal vasculature and the positive pneumoperitoneum used in laparoscopic surgery contribute to the absorption of the toxic chemicals. To minimize intracavitary smoke absorption in any gaseous environment, the intracavitary pressure in our system can be kept very low and controlled precisely at any level using the integrated pressure sensor.

Furthermore, because of the closed circuit of gas in our system, the surgeon and the operating room personnel theoretically do not experience any smoke exposure. The potential hazards of surgical smoke for operating room personnel include genotoxicity, pulmonary irritation, and transmission of infection. In our system, the entire surgical plume is completely evacuated and filtered.

Using dry and cold gas in laparoscopy has been shown to cause severe desiccation and peritoneal damage [27]. High flow rates, as used in our system, would worsen that problem. Due to technical reasons we used only dry gas in our laboratory experiments. For a future industrial device, it would be necessary to add applications for gas conditioning (i.e., humidification and warming of the gas).

In our study we tried to minimize the size of the ports/trocars and the intracavitary volume in order to exploit minimally invasive procedures used in both new and established endoscopic microsurgery techniques in the fields of intraorbital surgery [10], intraocular surgery [28], head and neck surgery, brain surgery, intravascular

microsurgery, and other surgical operations. Our approach involved maximizing the flow rate through the cavity using minimized ports. The main technical restrictions for minimization are the tube diameters for gas inflow and outflow. The maximum possible gas flow in the inflow or outflow tube (trocars) depends primarily on the tube diameter, tube length, and pressure applied from the outside. While the maximum pressure for the inflow tube can be increased without limit, there is a theoretical maximum of -1 bar (vacuum) available for the outflow tube [18]. This value sets the limit for miniaturization. For example, we experimentally found a maximum outflow of 2 l/min for a 20-G tube (length = 50 cm, applied vacuum = -0.8 bar) [18].

In future evacuation devices, the insufflation and suction tubes might be conducted separately to the endoscopic cavity, as shown in our experiments. Depending on the application, however, they could also easily be incorporated into a single endoscope. However, future devices must be developed and tested.

Our system could easily be adapted to a larger size depending on the application (e.g., laparoscopy, mediastinoscopy, cystoscopy, hysteroscopy, or thoracoscopy).

Our experiments also showed that the smoke evacuation tube can easily become blocked by tar and soot. This problem is particularly important in very small tubes when high volumes of smoke transit the tube. We report on a special technique to overcome this problem. Small amounts of sucking aid liquid (BSS) are continuously injected onto the front face of the smoke evacuation tube. The smoke and the liquid are sucked together into the smoke evacuation tube. The liquid binds to the smoke particles, which otherwise would stick to the evacuation tube walls and gradually choke the tube. The technique was shown to be useful even under conditions of very heavy smoke formation (e.g., laser vaporization). The diameter of the tube can be as small as possible in order to minimize the endoscope's diameter. The device in our experiments is a very simple laboratory model that can be modified for any endoscope. Fluid could be injected by a nozzle in front of the suction tube of any endoscope. In addition to its usefulness in endoscopic procedures, this new suction technique can be adapted for use in other surgical smoke-sucking devices to prevent blockage.

The results of our experiments demonstrate a positive potential for a new, minimally invasive technique for laser and other smoke-producing endoscopic operations. However, due to the experimental nature of our study and the devices used, further studies on animal and human cadavers with technically improved industrial devices (including gas conditioning) are required to reveal all possible fields of application and define the technique's advantages and limitations.

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